# Manual for the Carbo* Models of Marine Carbonate Sedimentation

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## 1 Summary

The Carbo models are a loosely coordinated set of numerical simulations of marine shallow-water carbonate production and sedimentation. Each employs a different type of mathematics to examine the issue: CarboCAT – cellular automata, CarboCELL – cellular modeling, CarboLOT – Lotke-Volterra calculus.

# 2 Introduction

## 2.1 Software environment

a. Windows 7 Home Premium 64-bit Operating system
b. Pentium Dual Core CPU, 2.7GHz, 3.75GB useable RAM
c. Python 2.6.# through the IDLE v2.6.6 IDE
d. Python modules Matplotlib, Numpy and Scipy
e. MS Excel for managing the Organism Knowledge Base (OKB)

## 2.2 Dependencies

a. CarboMODELS can be installed in any folder location. All addresses are relative to the home folder "_carboMODELS/".
b. In the same folder as _carboMODELS there needs to be the folder "dbSEABED/" holding the environmental data structures of "dbSEABED/_db9/_Enviro/" and "dbSEABED/_db9/_Bathy/"

## 2.3 Conventions

a. Nulls:
   i. 10^-4 is the minimum value for organism stocks
   ii. -99 and -99.0 are the integer and float Null values; "-" is the string Null.
   iii. 1.0E-04 is the floor and null value for organism stocks expressed by occupied area.

# 3 CarboKB – Organism Knowledge Base

## 3.1 Rationale

a. Population modeling requires knowledge of at least some crucial features of the organism's reproductive, growth and survival strategies. Implementing this has been a disincentive to population modeling for corals and thin-knowledge models have been written as a response to the problem (REF##).

b. The carbo* models however must be supported by this kind of knowledge, and information on the nature of the skeletal frames and products. For the purpose, and to address work flow issues of labour and accuracy, a knowledge base has been designed, which is a combination of tabulated inputs and software to interpret those inputs. The result is that researchers have a deal of flexibility in how data is entered, which is necessary when the data in papers and reports is to be entered. The program then brings that data into conformance (e.g., in units, meanings) by applying a set of agreed rules. This way of proceeding is important because: (i) the process is self-documenting and leaves an audit trail (in the program versions); (ii) the processes can be updated and/or extended as experience is gained with program results and newly incoming input datasets.

## 3.2 Structure

a. The Knowledge Base is managed in the folder **C:\Carbo2011_carboKB**.

b. The data that forms the Knowledge Base is compiled in EXCEL, in a file of name "_carboKB_#.xlsx" (# is version, currently '7'). (The leading underscore shows that the file is required in the carbo* modeling software.

c. The KB table layout is:
    i. The marker symbol "|" in the first and last columns, defining the table limits (necessary in working from EXCEL);
    ii. Documentation, in lines headed by '#';
    iii. Organism titling lines;
    iv. Data columns: parameterName, parameterValues, parameterUncerts, parameterUnits, dataDetails, parameterDetails, sourceReferences;
    v. End-of-data flag: "ALL_END".

d. The parameters are given names in DataStructure type of syntax: organism.subject.parameter. This organization is followed (loosely) in the attendant programs.

e. Restrictions. No Tabs or EndsOfLine may be used within data entries. Use of Pipe ("|") in lines may produce unpredictable results. Data entered to the right of column 8 will produce an error in program runs, as will failure to have "|" for columns 1 and 8.

f. At date 16 May 2011 the list of parameters per organism is:

| | |
|---|---|
| **Organism=** | |
| .AlternativeTaxa | other names/organisms included |
| .Size | linear size (diam) |

| | |
|---|---|
| .Occupancy | Observed areal coverages |
| .Tissue.AreaFraction | Areal fraction (vertical view) of living tissue |
| .Skeleton.AreaFraction | Areal proportion of skeletal frame (view vertically) |
| .Skeleton.GrowthRate | linear extension |
| .Skeleton.Morphology | Descriptive |
| .Skeleton.Zonation | [%Presence] Set |
| .Skeleton.Disintegrated.Fraction | Fraction volume it will disintegrate to after death/transport/burial |
| .Skeleton.Disintegrated.Grainsize | Clast/grain size after death/transport/burial |
| .Enviro.Threats | Limitations on growth/fecundity/survival |
| .Enviro.Prefs | Preferences for growth/fecundity/survival |
| .Enviro.Range.irrad | [EnviroParam, Fitness] LineSet |
| .Enviro.Range.salin | [EnviroParam, Fitness] LineSet |
| .Enviro.Range.nutr | [EnviroParam, Fitness] LineSet |
| .Enviro.Range.temp | [EnviroParam, Fitness] LineSet |
| .Enviro.Range.wd | [EnviroParam, Fitness] LineSet |
| .Enviro.Range.oxygen | Dissolved Oxygen |
| .Mortality.Longevity | Maximum, usual lifespan |
| .Mortality.Rate | Rate of natural, unexplained mortality |
| .Mortality.Type | Causes of mortality even in optimum conditions (e.g predation, dieback) |
| .Repro.Clone.ProductionRate | Clones produced per adult per year under normal conditions |
| .Repro.Clone.SuccessRate | Successful formation of colonies from clones (e.g., unattached colonies) |
| .Repro.Clone.Type | Description of the method of cloning |
| .Repro.Spawn.MaturitySize | Organism/colony size to commence spawning |
| .Repro.Spawn.ProductionRate | Spawn (eggs, larvae) produced per adult per year |
| .Repro.Spawn.SuccessRate | Propagules surviving to grow; /m2 instantaneously |
| .Repro.Spawn.Type | Description of the process of reproduction; seasonality |

*Table ##. List of parameters in the Data Input Table*

g. LineSets. Environmental ranges can be given as line sets. An example is: "[35,0;75,50; 370,50; 500,100; 700,100; 850,50;3000,0]", where each pair is [environmental value, suitability in percent]. (In the OKB program, the suitabilities are normalized to maximum = 100%.) The graph of the example is shown below. LineSets are similar to the way memberships are represented in Fuzzy Logic.

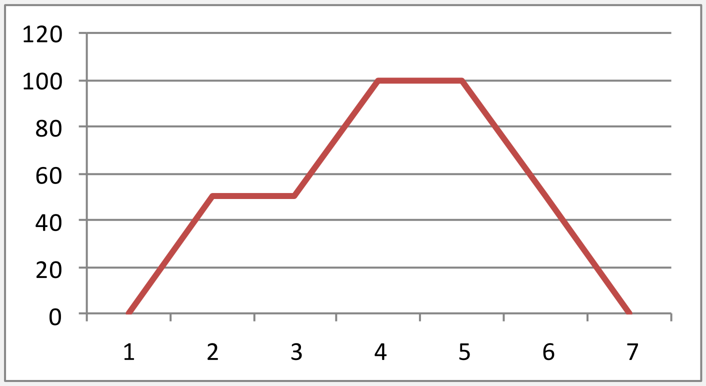



*Fig. ##. Visualization of a LineSet.*

f. Numeric syntaxes. A single numeric value can be entered, but there is a wider syntax giving more flexibility.
   i. Range using “>>” as in “3>>5”
   ii. Maximum, minimum, average, median using “mx=”, “mn=”, “av=”, “md=” as in “av=20;mx=90”. A semi-colon separates each entry.

These expressions are edited by the interpreter and converted to a numeric value with “eval” in Python. The examples convert to “(3+5)/2” (=4) and “(20 + 90*0.5)/2” (=35). The program treats maxima and minima as twice and half the output values, and averages and medians as equal to output values. The assumptions can be debated, but they produce quite reasonable results from even ragged input data.

## 3.3 Data Entry Methods

a. Usually data entry will be focused at any one time on a given organism and it’s close relatives. It is rare for all data to be available for one organism, and .AlternativeTaxa provides a place where related taxa which have also contributed to the information can be listed.
b. Data is either word-based or numerical.
c. Word-based data has “$” in the units column and applies to all descriptive entries. At a future time this word data will be parsed-analysed and meanings will be conveyed to the modeling programs. For the present this is done in a rudimentary way. (This type of process operates in dbSEABED.) For data entry, just enter the terms applying to the organism, separated by semi-colons (“;”). Commas may be used within phrases.
d. The field “.Skeleton.Zonation” has a separate syntax, a set of proportions of skeletal material in each of the four vertical zones: subfloor, floor, frame, superstructure. (Example: “[0;10;30;40]” for Acropora.) This is simply converted to an array of the same values for use in the model.

## 3.4 carboKB – The Interpreter

a. The program is called carboKB_#.py where # is the version number (currently ‘2’). It runs native in OS, or under IDLE in Windows.
b. Once the EXCEL table is satisfactory, save that page to file name of form “_carboKB_#.txt” (where # is currently ‘7’), as tab-delimited text.

c. The program has error traps for format and content, so running the file may produce error reports. Return to the EXCEL to correct the errors. (From experience, editing the exported text file is NOT recommended.)

d. The program produces a file "_carboKB_#.inp" which will be picked up by the next stage modeling programs.

## 3.5 FACIES table

a. A Facies definitions table is allowed for each project (e.g., _chag_FACIES.txt). This sets out which organisms and sediment textures are characteristric for the various facies which will be depicted in stratigraphic visualisations.

b. The arrangement of facies is:

| #Facies table 1 June 2011 CJJ | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| - | - | phormidium_crosbyanum | porites_lutea | acropora_palmata | acropora_cervicornis | favia_favus | halimeda_tuna | lithothamnion_corallioides | hydrolithon_onkodes | lophelia_pertusa | celleporella_hyalina | marginopora_vertebralis |
| - | - | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| coral–algal bindstone, | A | - | - | - | - | - | - | - | pri | - | - | - |
| mixed skeletal rudstone, | B | - | - | - | - | - | - | - | pri | - | - | - |
| massive coral framestone, | C | - | pri | - | - | pri | - | - | - | - | - | - |
| unconsolidated floatstone, | D | - | - | - | - | - | pri | - | - | - | - | pri |
| branching coral framestone–bafflestone | E | - | - | pri | pri | - | - | - | - | - | - | |
| microbialite | | pri | - | - | - | - | - | - | - | - | - | - |
| bioclastic sand | | - | - | - | - | - | - | - | - | - | - | - |
| bare ground | | - | - | - | - | - | - | - | - | - | - | - |
| halimeda banks | | - | - | - | - | - | pri | - | - | - | - | sec |
| rhodolith | | - | - | - | - | - | - | pri | pri | - | - | - |
| cold-water coral biostrome | F | - | - | - | - | - | - | | - | pri | - | - |
| cold-water bryozoal biostrome | G | - | - | - | - | - | - | sec | - | - | pri | - |
| END! | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| #Comments: | | | | | | | | | | | | |

Fig ##. An example of the facies definitions table.

This may be edited in the sheet _Facies_* of the file _carboKB_*.xlsx.

c. The terms are: pri – primary, sec – secondary, neg – negative, req – required.

## 3.6 Required further development

TBD

# 4 CarboLOT – Calculus-Based Model

## 4.1 Applications

a. CarboLOT is able to produce modeled mappings and statistics for carbonate production, thickness through <1000yr time spans for modern marine settings. The map areas are typically <100km on side, with cellsizes <2km.
b. By drawing on global environmental data layers model setup time kept very small, about 1 hour.
c. The model produces a range of visualizations including maps, graphs, sections, in PNG format and a series of dumped data outputs which allow further products to be generated by users.

## 4.2 Structure

a. The model is conducted in **C:\Carbo2011_carboLOT**.
b. **carboLOT_#.py**: main Python program, built with Python 2.6. (The current version of carboLOT is '14'.)
c. **_aaaa_setup.txt**: file for input of project setup such as map dimensions, time bases, naming; (aaaa='CHAG' for Chagos Island project).
d. **_events_CJJ.txt**: file describe the various types of events, their severities and affected organisms.
e. **KB_n.txt**: Organism Knowledge Base describing the form, ecology, reproduction and taphonomy of organisms; (n=6).

## 4.3 Data Requirements

### 4.3.1 PrimaryStartUp grid inputs.

CarboLOT draws on a set of basic input gridded environmental layers from the dbSEABED environmental collection. These apply to the map area at start-up. Concievably, an environmental history might alter them through time (but that facility not implemented yet). They are used to compute the environmental parameters for the grid cells.

a. Irradiance: MODIS AQUA for the modern ocean, local in **C:\dbSEABED_db9_Enviro_Light**
   i. chlorophyll-a: **SDS_l3m_CHL.dat** 35.5MB
   ii. ## **SDS_l3m_FLH.dat** 35.5MB
   iii. ## **SDS_l3m_PAR.dat** 35.5MB
   iv. ## **SDS_l3m_RRS.dat** 35.5MB.
b. Bathymetry: GEBCO global gridded elevations (water depths and altitudes), as little-endian i4 ('<i') binary grid **C:\dbSEABED_db9_Bathy\GEBCO_1nm\GridOne.grd** 890MB with ascii header file **GridOne.hdr** 569B
c. Bottom Water Temperature: from the World Ocean Atlas 2005 (WOA05) local in **C:\dbSEABED_db9_Enviro\WOA\IRIDL\Temp\decdata.r4** 32MB , a simple binary grid in little-endian float4 ('<f')

d. Wave climate from WAVEWATCH III Model local in **C:\dbSEABED_db9_Enviro\wwIII** simple binary files for annual average Significant wave height (m) hsNWW3.grd 3.44MB, Peak wave period (secs) , and Peak wave direction (deg) dpNWW3.grd 3.44MB.

### 4.3.2 Derivative grids

Derivative gridded sets are generated as the topography changes in the modeled area. They are the grids written to the _enviro_ dump.

## 4.4 Run instructions

a. Open the program in IDLE, press F5. The scrolling screen display details setup results which can be cut-pasted to documents.
b. Answer pauses with:
    i. a project code corresponding to one of the files **_aaaa_setup.txt** . This operation will create the working project folder structure.
    ii. y/n to freshly compiling the subsets of the environmental data; mostly they can be re-used from previous runs. Re-compile them when the project grid or environmental grid stacks are changed in anyway.
c. The program runs to completion. Maps and environmental summaries are computed while underway. The final stage reads from dumped results to compute the graph outputs.

## 4.5 Formulation

### 4.5.1 General

CarboLOT has a competition Lotke-Volterra formulation, with attendant functions treating growth, calcification, etc. All stocks are rated against 1.0, which is 100% areal coverage by the live parts of the organism.

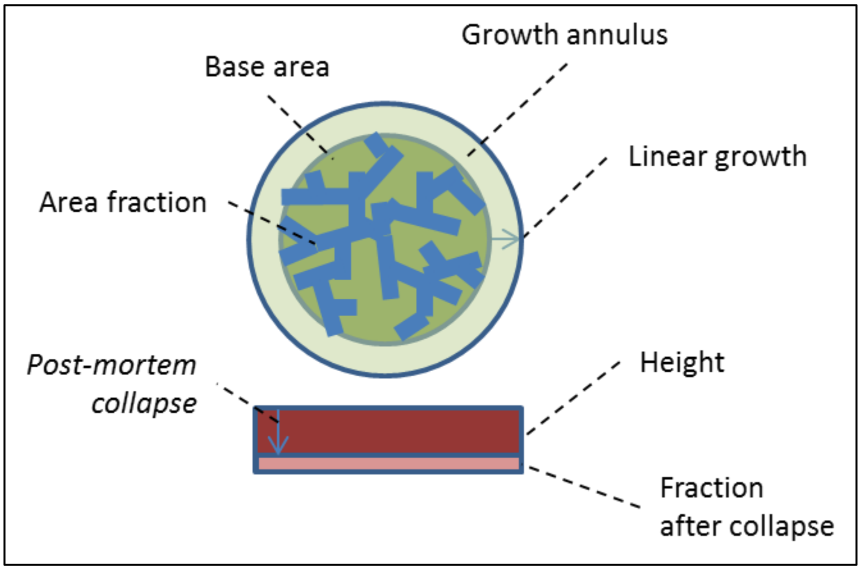
### 4.5.2 Habitat Suitability

i. A set of linesets is available per organism, to quantify suitability per environmental parameter. The parameters are currently: temperature, depth, irradiance.
ii. The intersection of cell environment with these linesets produces a set of suitabilities ( [$s_{temp}$, $s_{wd}$, $s_{irrad}$] ). The consensus suitability S, is calculated as their median, but other choices are possible. It is $\mathbb{R}[0.0,1.0]$.
iii. For L-V, Carrying Capacity (K) is equated to the Suitability.

### 4.5.3 Growth

iv. Growth is scaled against a number of sources. First, linear extension rates are obtained from the OKB in units of m/yr. Second, those rates are discounted by the organism's Suitability in the cell ($S_{y,x}$).
v. The linear growth is recalculated to an annulus extending the organism base area (which is based on diameters given in the OKB).

vi. The thickness increase (carbonate frame plus included voids) is calculated from the annulus, discounted by the fractional areal coverage of the organism. (For example, *Porites* is counted as 1.0, *Lophelia* as 0.2 .)




## 4.6 Output Folder/File Structures

a. The project is created under **C:\Carbo2011\carboLOT**. With subfolders:
   i. **_DataDumps**: data written per time-step for stocks, etc.
   ii. **_MapPlots**: for all spatial displays
   iii. **_GraphPlots**: for all plots of time-series results
   iv. **_Setup**: for the start-up environmental layers subset to the project area; runs may read these in instead of re-compiling.
b. In _DataDumps:
   i. _populo_n n.txt: the time-series of organism stocks for each map cell with format: "YX=6 3; T=13.0; Stocks=0.0001 0.0001 0.0001 0.0001 0.0001 0.0001 0.0001 0.0001 0.755218658623 0.0001"
c. In dumps of map values the cells are written rows=yMax to 0, and columns=0 to xMax, which is inverted in the vertical from true geographic patterns. This probably should be changed (future).

## 4.7 Form of Outputs

a. The program writes output for each time step in mapwise form, to the folders:
   i. "_StockDumps": population stock per organism "_populo_0_0.txt"; environmental conditions "_enviro_20.rep";
   ii. "_StratDumps": carbonate accumulation "_prodn_25.txt"; stratigraphic thickness/buildup "_thickns_9.txt"; facies "_litho_4.txt".
b. Some of these files are read through the processing, and also at program end when to make the stratigraphic diagrams.
c. Graphical outputs are produced at certain time steps ('Reporting' steps; "#") in these folders:

i. "_MapPlots" (through program run): dominant organisms and their stocks "PRJ_DomOrgnsms_t#.png"; the total stocks of all organisms (not including vacant) in "PRJ_orgStockSum_t#.png"; the carbonate production of the time-step "PRJ_CarbProdn_t#.png"; the carbonate thickness/buildup of the time step "PRJ_CarbThickns_t#.png";

ii. "_GraphPlots" (at end of program run): time-series of the stock at selected cells, usually along a section through the map "chag_stocks_4yx0_2053wd.png"; a stratigraphic cumulative thickness traverse on the same section "PRJ_strat.png".

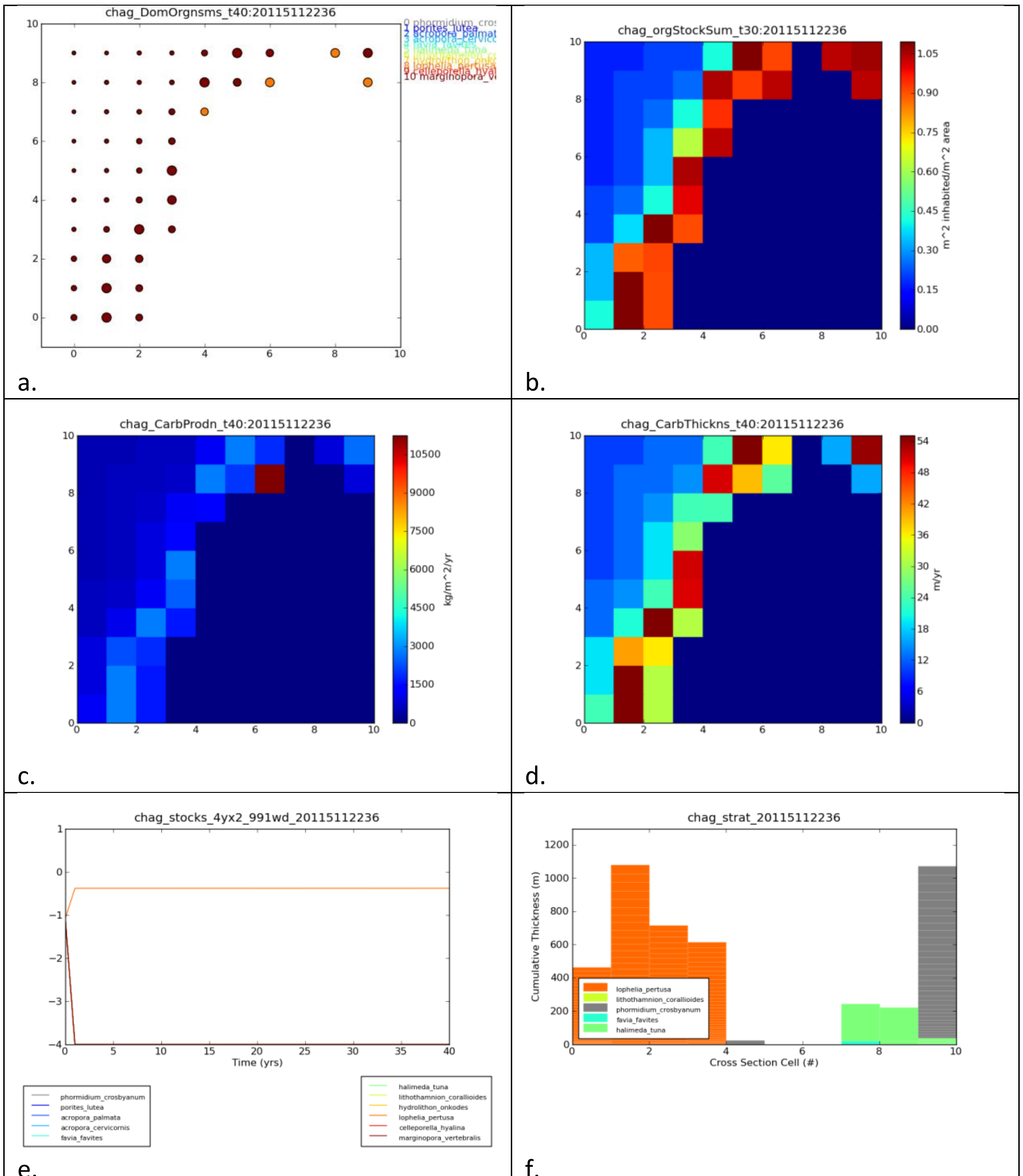



*Fig. ##. Graphics produced from carboLOT. Panels: a. Dominant Organism/facies and their stocks; b. sum of all the live stocks; c. carbonate production for the time-step; d.*

*accumulated carbonate thickness for the time step; e. Progress of the stocks for a map-cell; f. stratigraphic thickness coded by the dominant organisms.*

## 4.8 Required further development

a. Extend the types of supporting environmental data layers – e.g., salinity, bottom currents, wave climate.
b. Develop an interface to GIS-produced data so ancient scenarios can be investigated.
c. Generate lithological core-logs showing dominant preserved organisms; calculate statistics of heterogeneity for the simulated carbonate sediments.
d. Hyperbolic interpolation of environmental data layers.
e. Extend the OKB to a greater number of organisms, and in each a fuller set of parameters.
f. Validation studies against ecological transects, remote sensing data, and drill-core.
g. Virtual globe (KML) displays of the project setup and results.

# 5 CarboCELL – Cellular Model

## 5.1 Rationale

a. Cellular modeling is performed in a similar way as Cellular Automatons, but the rules are more open, with the possibility of stochastic and complex numeric operations. The map retains wrap-around and is updated only after the whole map-wise result is completed.
b. CarboCELL is a small process that could be embedded as a micro-calculator in a wider model process like carboLOT. It is run per mapcell at present, but in the future could be run selectively at map points and for distinct facies.
c. Only one organism occupies a cell, and actually, a cell may represent a facies rather than an organism. For example, cell '0' is "vacant cells" representing a facies of BareGround.
d. CarboCELL is inspired by, and can run a Python version of carboCAT by P. Burgess.

## 5.2 Structure

a. The program operates from **C:\Carbo2011_carboCELL**. The program is labeled "carboCELL_#.py", and is currently at version '5'.
b. The folder "_Dumps" takes written outputs from the model, per time step.
c. The folder "_Movies" hold a GIF movie which is compiled at program end from the collection of time-step PNG graphics.

## 5.3 Operation

a. To begin a run, decide a run name (say: "PRJ"). The program will automatically produce all the required folder/file structures, such as "/_PRJ/_Dump/" for the run results.
b. A grid layout is set from the program in terms of cell count. It is not geographically located. (Note: a file "_setup_PRJ.txt" is needed which can define a project outside the program.)
c. A rudimentary set of definitions is given for the organisms and events, from the setup files "_facies_PRJ.txt" and "_events_PRJ.txt", representing a run/project.
d. At program end a series of graphics is produced:
    i. "facies_model_PRJ_#.png" where # is the timestep;
    ii. "ages_model_PRJ_#.png";
    iii. (optionally) "correl_PRJ_#.png";
    iv. "stats_model_PRJ_#.png" where # is total run length;
    v. "strat_model_PRJ_#.png".
e.

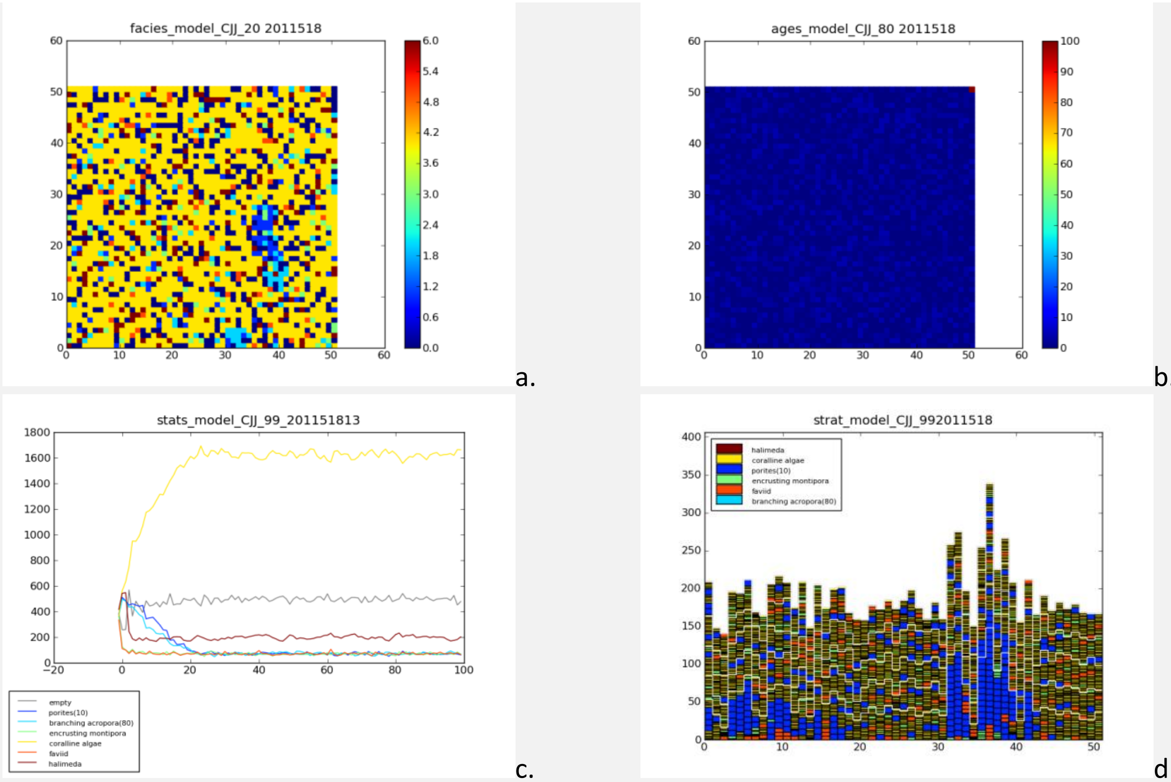



*Fig. ##. Graphics produced from carboCELL. Panels: a. Organism/facies patchiness at time step (20); b. ages of the organisms/facies at a time step; c. Time series plot of the populations (cell counts) of each organism/facies; d. Stratigraphic thickness for a section of the map (horizontally, middle).*

## 5.4 Required further development

TBD

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# 6 References

Engels, M.S., Fletcher, C.H. III, Field, M.E., Storlazzi, C.D., Grossman, E.E., Rooney, J.B., Conger, C.L. and Glenn, C. 2004. **Holocene Reef Accretion: Southwest Molokai, Hawaii, U.S.A.** JOURNAL OF SEDIMENTARY RESEARCH, VOL. 74, NO. 2, MARCH, 2004, P. 255–269