

Upper level course

ATMOS/GEOG/GEOL 397E "MODELING THE EARTH SYSTEM"
3 hours or 1 unit

Wednesday 7-10 pm (given the late hour, rides will be available for students after class) Room 219 Atmospheric Sciences Building.

ONLY EAST ENTRANCE TO BUILDING WILL BE UNLOCKED AT 7.

Optional open lab: Tuesday, 3-5 pm, Room 219 Atmospheric Sciences Bldg

Instructors

Prof. Thomas Anderson, Department of Geology, 234 Natural History Building
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Teaching assistant

Mr. Geoff VanDyke, Department of Geography, 124 Davenport Hall
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Geoff will be at the Tuesday open lab sessions

Texts (required)

Donella H. Meadows, Dennis L. Meadows, Jørgen Randers, *Beyond the Limits: Confronting Global Collapse, Envisioning a Sustainable Future*
 Arthur A. Few, *System Behavior and System Modeling*

Welcome to ATMOS/GEOG/GEOL 397E, "Modeling the Earth System". In this course you will build and use models of global climatic, hydrologic, geochemical, and human systems, explore the basic concepts of systems modeling, use models to test hypotheses, and find out about the assumptions and approximations that must be made in modeling. Your models will be constructed using the STELLA® modeling software on Macintosh computers. STELLA offers an intuitive approach to modeling, so that prior experience with computer modeling is *not* a prerequisite for this course.

Why bother to learn about models and modeling? First, because models have become the primary research tool in trying to understand and make predictions about global systems. Many of you will use models in your future research. At the very least your research will be motivated by and informed by results from models. Secondly, because decision-makers use models, and their decisions affect directly how you, and everyone else, lives their lives.

In the past, in various courses, the instructors of this course have described models and presented results from models. Modeling, is, however, only learned by doing. So, this is a course where you will spend most of your time building and

using models. The goals are several:

- ◆ to understand how models are constructed and used, what assumptions must be made, which results are robust and which are deserving of skepticism...
- ◆ to grasp the fundamental systems concepts that underlie all models: fluxes and reservoirs, positive and negative feedbacks, open and closed systems...
- ◆ to gain basic modeling skills that can be applied in your own research...
- ◆ to learn about the basic principles that govern the systems we model here: the climate, the hydrologic cycle, biogeochemical cycles, and the sustainability of human activity on the earth.

Organization and grading

Throughout the semester you will work in small groups. Initially these will comprise just two or three students. Because of the widely varying backgrounds, modeling experience, and computing expertise students bring to this course, these groups will be assigned by the instructors, and they will change over the course of the term. For the first 3 sections of the course, hydrology, climate, and biogeochemical cycles, your group will be asked to keep a lab notebook, describing your models and the experiments conducted with them. For the final section, global sustainability, you will formulate questions to pose to the "World3" model, and then present your results to the class. Grades will be assigned on the basis of these notebooks and presentations.

Use of the texts

There are two required texts. The first of these, Arthur Few's *System Behavior and System Modeling*, will be most useful early in the semester. You should read through the brief (48 pages) of the body of the text during the first week of the semester. The remainder of the book is a "Quick Help Guide" for STELLA (starts on page 88) which may be of use throughout the semester, and a STELLA tutorial (pages 58-82). The deer population model you construct in this tutorial is a simpler example of the overshoot and collapse dynamics that are at the core of the most alarming predictions of the World3.

Beyond the Limits, by Donella Meadows, Dennis Meadows, and Jørgen Randers, introduces the ideas behind the World3 model, and goes on to describe what this model tells us about the future of human society. This is a very readable book, and it is essential that you read it before the final section of the course begins in April. You are *not* required to agree with the book. In fact, as you read, you should be thinking about which of the authors' assumptions you question. Such doubts can motivate your later experiments with World3.

Additional readings may be assigned during the semester.

Schedule

Date	Topic	Principal instructor
Jan 22	Intro. to course, modeling and STELLA	Robinson
Jan 29	Hydrology models	Robinson
Feb 5	" "	" "
Feb 12	" "	" "
Feb 19	Climate models	Robinson
Feb 26	" "	" "
Mar 5	" "	" "
Mar 12	Biogeochemical cycles	Anderson
Mar 19	" "	" "
Apr 2	" "	" "
Apr 9	" "	" "
Apr 16	Global sustainability	Isard
Apr 23	" "	" "
Apr 30	" "	" "
May 7	" "	" "

"Modeling the Earth System": a New Interdisciplinary STELLA®-based Course at the University of Illinois

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Models have become a key tool for understanding and making predictions about global systems. Most students have little experience in building and using models of natural systems. Gaining such experience is necessary if they are to use models in their research, or to evaluate scientific results and policy decisions that are model-driven.

A new course, "Modeling the Earth System", has been developed at the University of Illinois to provide this experience. It is taught cooperatively by the departments of atmospheric sciences, geography, and geology. Students build and use models of global climatic, hydrologic, geochemical, and human systems. They explore the basic concepts of systems modeling, use models to test hypotheses, and find out about the assumptions and approximations that must be made in modeling complex natural systems. Models are constructed using the STELLA® modeling software. STELLA® offers an intuitive approach to modeling, so that prior experience with computer modeling is not a prerequisite.

Goals are for students: to understand how models are constructed and used, to grasp the fundamental systems concepts that underlay all models, to gain basic modeling skills that can be applied in their own research, and to learn about the systems they model.

Modeling the Earth System

a New Interdisciplinary STELLA®-based
Course at the University of Illinois

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Course development funded by the Universities Space Research
Association, Earth System Science Education program

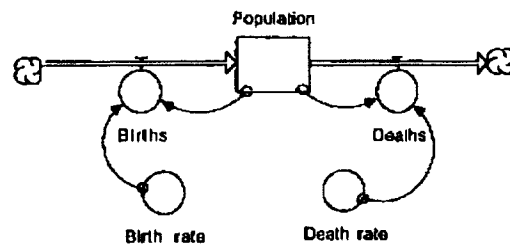
Why teach modeling?

- ★ Knowledge of earth system is model-based
- ★ Future research will involve models
- ★ Policy is model-driven

★★ *Most students*★★
don't know what a
model is

What is STELLA®?

Systems modeling
software for personal
computers (PC or Mac)
with intuitive graphical
interface



Why STELLA®?

- + Easy to learn
- + Graphic representation of models
- + Programming experience not needed

Why not STELLA®?

- Not good for space/time PDE's
- Simple numerics poor for some problems
- Not transferable to workstations - big models run slowly on Mac/PC
- Students think it's not *real* modeling

Course Goals

- ★ What's a model?
- ★ How do you build one?
- ★ Warts
- ★ Systems thinking
- ★ Specific topics

What we did

wks

- 1 Warm-up problem
- 3 Hydrology
- 3 Climate
- 4 Carbon cycle
- 4 World3

Texts

System Behavior and System Modeling

Arthur A. Few
University Science Books 1996

Beyond the Limits:

*Confronting Global Collapse,
Envisioning a Sustainable Future*
Donella H. Meadows
Dennis L. Meadows
Jørgen Randers
Chelsea Green Publishing Co. 1992

Format

One 3-hour meeting/wk

Half-hour lecture on
week's problem

Handout posing problem

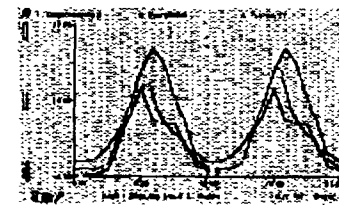
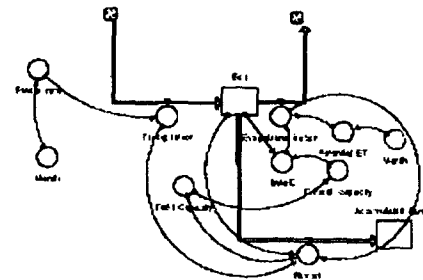
Work in groups

Turn in report following
week

Oral reports on World3

Sample problem

"Bucket" model for
surface hydrology

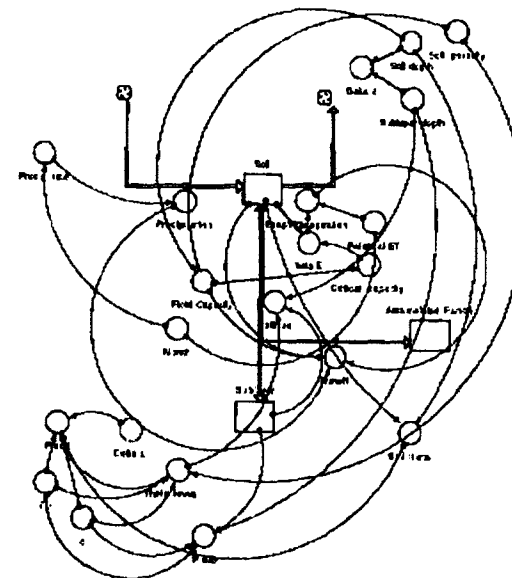


What worked?

- + Hands-on approach
- + STELLA®
- + Pairs
- + 1 long meeting/wk
- + Simple models
- + World3

What didn't work?

- Complicated models



What didn't work? (cont'd)

- Systems concepts only
by example
- Too many models
- Groups > 2

Student critique

Hard work

Little concrete learning
Want more lectures

STELLA isn't real modeling

Frustrations of group work

Next year

*Explicit intro. to systems
concepts*

*Students do more
pre-STELLA® model
development*

Fewer models

*More depth in
experimenting with
models*

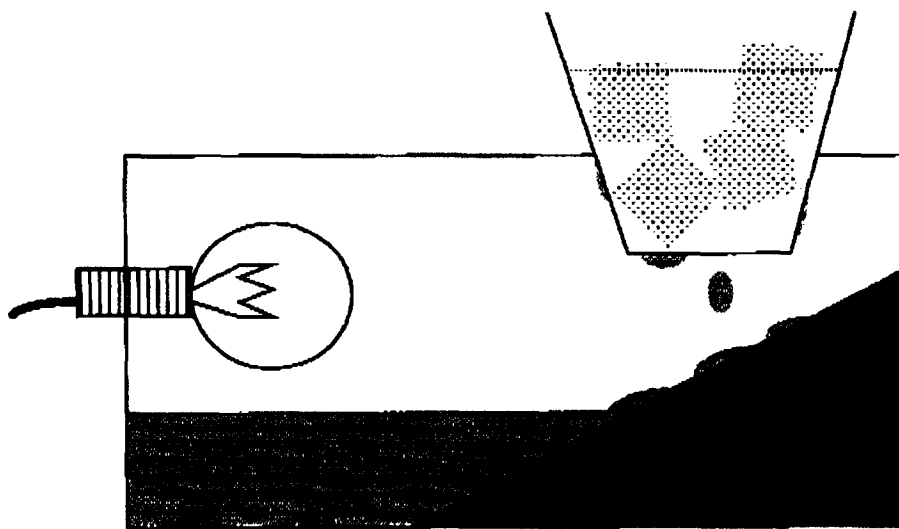
More readings

Modeling Project 4 – Global Hydrology in a Shoebox

The global hydrologic cycle, unlike our local hydrologic models, is nearly a closed system (there are minor chemical sources and sinks of water). Water exists in a number of reservoirs on the earth: the oceans, glaciers and snowpack, groundwater, lakes and streams, and in the atmosphere. Some reservoirs have very long timescales for their recharge, but within the most active elements of the hydrologic cycle—evaporation, condensation in clouds, precipitation, and runoff back to the ocean—water is nearly conserved.

A model of the global hydrological cycle is necessarily a model of the global climate system. While we will model the climate in the next section of this course, a detailed model of a realistic hydrological cycle is in the realm of atmospheric general circulation models (GCMs) and is beyond our scope. Rather, we confine ourselves to simulating the behavior of a much simpler system that we can take as a metaphor for the global hydrologic cycle. It includes the essential elements of evaporation, condensation, precipitation, and runoff.

A hardware version of this shoebox model will be brought to class. Here is a schematic diagram.



Heat is supplied by a light bulb—the "sun." Water evaporates from the "ocean." In the "atmosphere" water vapor is transported to the "cloud" (the outer surface of a cup of ice water penetrating the top of the shoebox) where it condenses. When there is sufficient liquid water on the cup it drips off as "precipitation," runs off down the "land," and returns to the "ocean." Building a STELLA model of this system reveals some of the fundamental issues in modeling the hydrologic cycle and introduces ideas we will need in our subsequent modeling of the climate.

To model the shoebox we must first recognize that there are two relevant quantities flowing through it. Water flows in a closed loop from the ocean to the

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atmosphere to the cloud and back to the ocean. Energy flows as electric power supplied to the lightbulb. The lightbulb heats the system. Heat is lost by conduction to the surface of the cloud. When water condenses on the cloud, it gives up its latent heat of condensation to the cloud, and this energy is also lost.

The energy cycle influences the hydrologic cycle, because the temperature determines the amount of moisture in the air at saturation and, thus, the rates of evaporation and condensation. The hydrologic cycle influences the energy cycle through evaporative cooling.

How to model this system

While the shoebox is enormously simpler than the earth's climate and hydrologic systems, it is still very complex. To make the problem tractable I made several assumptions. Other approaches are certainly possible, and I would be delighted to hear your ideas

Temperatures

Assume the whole model, except for the cloud, is characterized by a single temperature. The temperature of the cloud is fixed at the temperature of ice water, approximately 0 °C, or 273.15 K.

Heat flow

Assume heat enters only from the sun, and leaves only through the cloud.

Transport

As we will see later the biggest problem in constructing a simple climate model is treating the transports of heat and moisture. The transports in the shoebox depend upon the flow of air, the modeling of which is beyond the capabilities of STELLA and the scope of this course. Here we assume, with little justification, that the transports of heat and moisture are diffusive.

Heat capacity

This is needed to relate energy to temperature. Assume that the heat capacity of the atmosphere is negligible, so that the total heat capacity is simply that of the ocean.

Technical details—Hydrologic cycle**Evaporation**

A thin layer of air at the surface of the water is saturated. The rate of evaporation depends on how fast this moisture diffuses up into the atmosphere. The rate of evaporation (in kg H₂O/second), is then given by,

$$E = \text{Area}_{\text{ocean}} * (q_{\text{saturated}} - q_{\text{atmosphere}}) * \text{Density}_{\text{air}} * V_{\text{diffusion}} \quad (1)$$

Here the q's are the mixing ratios of moisture in the air in units of mass of water per mass of air. The mass of water vapor in the atmosphere is then,

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$$M_{\text{vapor}} = q_{\text{atmosphere}} * \text{Volume}_{\text{atmosphere}} * \text{Density}_{\text{air}} \quad (2)$$

Given the temperature, T , the mixing ratio at saturation can be calculated using an approximate form of the Clausius-Clapeyron equation,

$$q_{\text{saturated}} = q_0 \exp [T_1 * (1/T_0 - 1/T)] \quad (3)$$

(Values for the various constants are given at the end of this handout.)

The quantity, $V_{\text{diffusion}}$, in equation (1), is an effective velocity for diffusion. The diffusive transport of vapor into the atmosphere is equivalent to that from moving a column of saturated water, with area equal to the surface area of the ocean, into the atmosphere at this speed. There is little physical basis for choosing this number—values in the range of millimeters to centimeters per second (.001 to .01 m/s) seem to give reasonable answers. Try different values.

Condensation

This is treated similarly to evaporation.

$$C = \text{Area}_{\text{cloud}} * (q_{\text{atmosphere}} - q_{\text{sat. cloud}}) * \text{Density}_{\text{air}} * V_{\text{diffusion}} \quad (4)$$

The area of the cloud is that surface area of the cup that is within the shoebox. The saturation mixing ratio for the cloud is given by,

$$q_{\text{sat cloud}} = q_0 \exp [T_1 * (1/T_0 - 1/T_{\text{cloud}})] \quad (5)$$

Precipitation

This is essentially a "bucket" model. Assume that the water drips off the cup when the thickness of the layer of liquid water on the cup reaches a critical level, say 1 mm. Then the cloud is "full" and precipitation must balance condensation.

Runoff

I assumed that the precipitated water runs off immediately into the ocean, but you could include a hydrologic cycle for the "land" in your model, with a field capacity and the possibility of evaporation from the land.

Technical details – energy budget**Solar heating**

Assume all energy from the lightbulb remains in the shoebox. Thus, the rate of energy input is the wattage of the bulb. This is the "solar constant" for this model.

Conductive cooling

Conductive cooling occurs only at the cloud, and is governed by a diffusion equation like equations (1) and (4) above.

$$\text{Cooling}_{\text{conduction}} = \text{Area}_{\text{cloud}} * (T - T_{\text{cloud}}) * c_p * \text{Density}_{\text{air}} * V_{\text{diffusion}} \quad (6)$$

Here c_p is the heat capacity of air at constant pressure.

Evaporative cooling

Evaporative cooling is given by the rate of evaporation times the latent heat of condensation,

$$\text{Cooling}_{\text{evap}} = L * E . \quad (7)$$

Condensational heating

Condensational heating is not present, because this heat is lost to the cloud, which is held at a fixed temperature.

Relating energy to temperature

Temperature and energy are related through the heat capacity of the whole model, which is assumed equal to the heat capacity of the ocean,

$$\text{Heat capacity} = \text{Density}_{\text{water}} * \text{Volume}_{\text{ocean}} * c_{\text{water}} . \quad (8)$$

The heat capacity of liquid water, c_{water} , is given below.

Time parameters

If you choose physical dimensions appropriate to the hardware shoebox, the model will run with a timestep of 10 seconds, and will achieve equilibrium in an hour or two of model time.

Questions

In addressing these questions, key parameters to vary are $V_{\text{diffusion}}$ and the "solar constant."

- 1) How does the model approach equilibrium? Are thermal and hydrologic equilibrium approached on the same timescale? Why, or why not? What parameters determine the timescale(s) of this model?
- 1') How does the hydrologic cycle behave if it is uncoupled from the energy cycle? (You can do this by running your model with a fixed temperature.)
- 2) The model loses energy at the cloud by conduction and condensation. Under what settings of the parameters are one of the other of these terms more important? Why?
- 3) We can define the "climate" of the shoebox as the temperature and the rate of precipitation. Explore the sensitivity of the climate to changing the parameters. Explain your results.

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Values of physical constants

$$c_p = 1004 \text{ J/[kg K]}$$

$$c_{\text{water}} = 4218 \text{ J/[kg K]}$$

$$\text{density}_{\text{air}} = 1.25 \text{ kg/m}^3$$

$$\text{density}_{\text{water}} = 1000 \text{ kg/m}^3$$

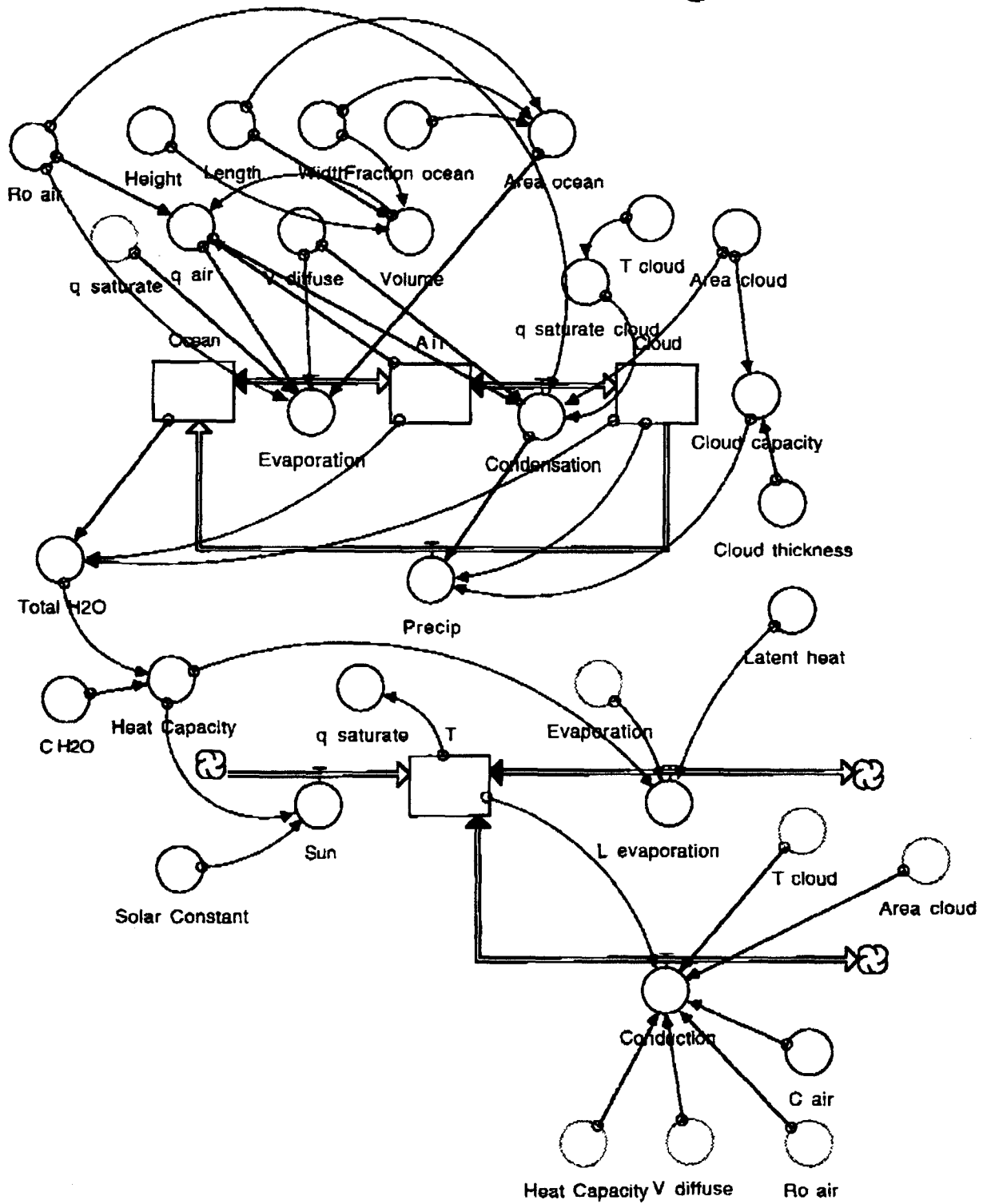
$$L = 2.5 \times 10^6 \text{ J/kg}$$

$$q_0 = 0.0038$$

$$T_0 = 273 \text{ K}$$

$$T_1 = 5423 \text{ K}$$

$$T_{\text{cloud}} = 273.15 \text{ K}$$



$$\text{Air}(t) = \text{Air}(t - dt) + (\text{Evaporation} - \text{Condensation}) * dt$$

INIT Air = 0

INFLOWS:

$$\text{Evaporation} = \text{Ro_air} * (q_saturate - q_air) * V_diffuse * \text{Area_ocean}$$

OUTFLOWS:

$$\text{Condensation} = \text{Ro_air} * (q_air - q_saturate_cloud) * V_diffuse * \text{Area_cloud}$$

$$\text{Cloud}(t) = \text{Cloud}(t - dt) + (\text{Condensation} - \text{Precip}) * dt$$

INIT Cloud = 0

INFLOWS:

$$\text{Condensation} = \text{Ro_air} * (q_air - q_saturate_cloud) * V_diffuse * \text{Area_cloud}$$

OUTFLOWS:

$$\text{Precip} = \text{if } (\text{Cloud} > \text{Cloud_capacity}) \text{ then Condensation} \\ \text{else } 0$$

$$\text{Ocean}(t) = \text{Ocean}(t - dt) + (\text{Precip} - \text{Evaporation}) * dt$$

INIT Ocean = .3 {kg}

INFLOWS:

$$\text{Precip} = \text{if } (\text{Cloud} > \text{Cloud_capacity}) \text{ then Condensation} \\ \text{else } 0$$

OUTFLOWS:

$$\text{Evaporation} = \text{Ro_air} * (q_saturate - q_air) * V_diffuse * \text{Area_ocean}$$

$$T(t) = T(t - dt) + (\text{Sun} - L_evaporation - \text{Conduction}) * dt$$

INIT T = 280 {K}

INFLOWS:

$$\text{Sun} = \text{Solar_Constant} / \text{Heat_Capacity}$$

OUTFLOWS:

$$L_evaporation = \text{Latent_heat} * \text{Evaporation} / \text{Heat_Capacity}$$

$$\text{Conduction} = \text{Ro_air} * C_air * (T - T_cloud) * \text{Area_cloud} * V_diffuse / \text{Heat_Capacity}$$

$$\text{Area_cloud} = .05 \text{ (m}^2\text{)}$$

$$\text{Area_ocean} = \text{Fraction_ocean} * \text{Length} * \text{Width}$$

$$\text{Cloud_capacity} = \text{Area_cloud} * \text{Cloud_thickness}$$

$$\text{Cloud_thickness} = .001$$

$$C_air = 1004 \text{ (J/kg)}$$

$$C_H2O = 4218 \text{ (J / kg /K)}$$

$$\text{Fraction_ocean} = 0.5$$

$$\text{Heat_Capacity} = \text{Total_H2O} * C_H2O$$

$$\text{Height} = .15 \text{ (m)}$$

$$\text{Latent_heat} = 2500000 \text{ (J / kg)}$$

$$\text{Length} = .40 \text{ (m)}$$

$$q_air = \text{Air} / (\text{Volume} * \text{Ro_air})$$

$$q_saturate = .0038 * \exp(5423 * (1/273 - 1/T))$$

$$q_saturate_cloud = .0038 * \exp(5423 * (1/273 - 1/T_cloud))$$

$$\text{Ro_air} = 1.25 \text{ (kg/m}^3\text{)}$$

$$\text{Solar_Constant} = 60 \text{ (Watts)}$$

$$\text{Total_H2O} = \text{Air} + \text{Cloud} + \text{Ocean}$$

$$T_cloud = 273.15 \text{ (K)}$$

$$\text{Volume} = \text{Height} * \text{Length} * \text{Width}$$

$$V_diffuse = 1.5 * 10^{-2} \text{ (m/s)}$$

$$\text{Width} = .20 \text{ (m)}$$

II. Visitors Invited/Funded Under the ESSE Program

a)

Name

University/Other Affiliation

None

b)

Contributions Made:

c)

What difficulties have you had in scheduling visitors?

III. Describe any interactions with NASA Affiliate (how often, benefits, etc.):

Visited Anthony Del Genio at NASA/GISS
~~on~~ July 1996. Obtained info on soil
hydrology models in GCMs, also GCM results
for climate change experiments. This info
was applied directly to both courses.

IV. What has been your principal role as PI of this project?

Teaching and organizing course development.
Obtaining university approval for courses.
Supervising T.A.'s