Modelling of Marine Systems. 1975. Jacques C.J. Nihoul (ed.). Elsevier Oceanography Series. Elsevier Scientific Publishing Co., N.Y. pp. 127-151.

CHAPTER 6

MARINE ECOSYSTEMS WITH ENERGY CIRCUIT DIAGRAMS

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6.1. INTRODUCTION

If the parts and processes of marine systems develop a unity of organization of physical, chemical, biological, and geological components to maximize the competitive use of energies available, an overview of these relationships is required for modelling and understanding. Separate modelling by components or by knowledge discipline may not suffice. Justification for these assertions were given in book form (Odum, 1971). If oceanic and atmospheric systems develop an interdependent order that maximizes power because of natural selection, the resulting pattern may involve interplay of all kinds of energies. The magnitudes of potential energy per area per year are as great in biological and chemical phenomena as in physical and geological processes.

Understanding the structure and function of marine ecosystems may be aided by diagramming and evaluating overall models with energy circuit language. This is a visual mathematics which uses energy as a common denominator for combining the models of chemical, physical, biologic, geologic, and economic subsystems. Diagrams help the comparative analysis of model configurations and are a useful interface between the mental concepts and computer simulation. In this review common elements of marine biogeochemical models are diagrammed and expanded in scope to include physical oceanographic terms. The methodology of defining macroscopic mini-models may encompass larger marine systems without increasing detail. Such models emphasize the structures and unity of organization that all systems build for maximizing their competitive survival through better processing. This is opposite from the modelling that fragments into a grid of nodes losing sight of the form and identities the system builds in itself. This chapter considers some uses of the energy language in portraying systems and aiding modelling.

6.2. USES OF ENERGY CIRCUIT LANGUAGE

First consider some examples of recent modelling as they look when

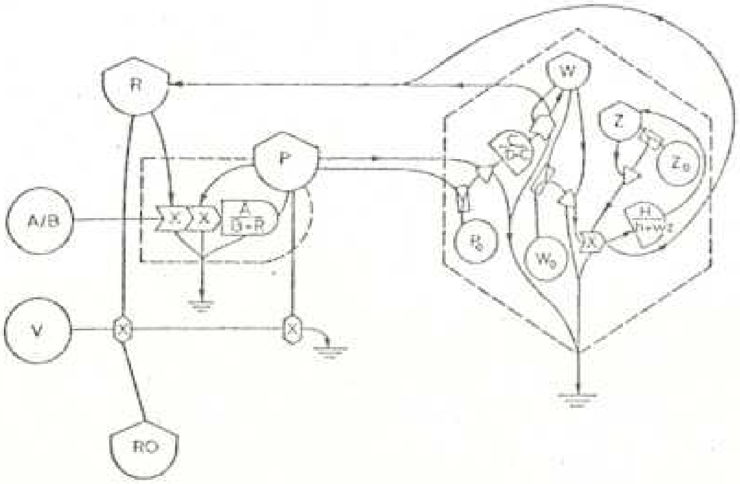


Fig. 6.1. Model for a plankton system translated into energese (from Steele, 1972).

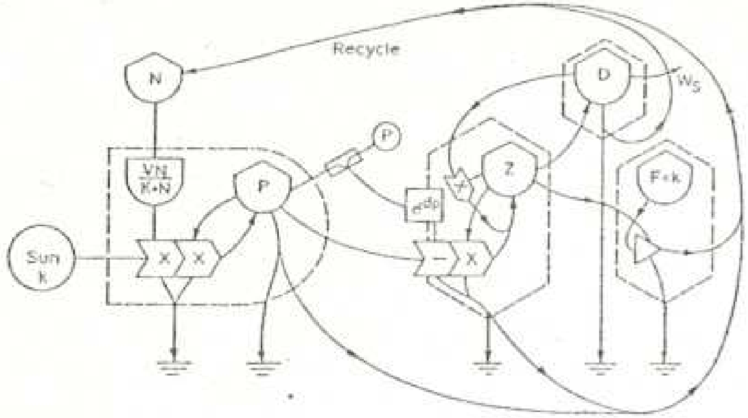


Fig. 6.2. Model for a plankton system translated into energese (from O'Brien and Wroblewski, 1973).

translated into energy circuit language. Figs. 6.1 and 6.2 are examples of a marine ecosystem model, one by Steele (1972) and one by O'Brien and Wroblewski (1973). The differential equations of these authors are exactly translated into the diagrammatic presentation in which each symbol has energetic, mathematic, and kinetic definition. An abbreviated list of symbols is given in Fig. 6.3. More complete discussions, premises, and conventions were given previously (Odum, 1971, 1972, 1973). In this review usual types of mathematical terms are written on the pathways of the diagrams, although this is an unnecessary redundancy, since the language already indicates these by the definitions of the symbols. Selected for this review are

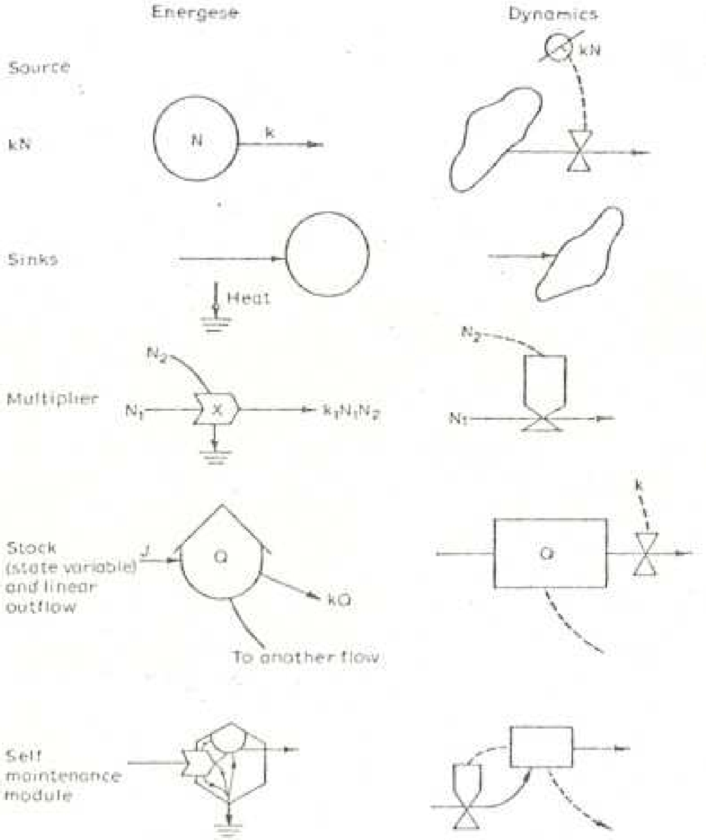


Fig. 6.3. Some main symbols of the energy circuit language compared with Forrester symbols.

discussions of those modules and configurations which were used in the NATO Conference on Modelling of the Sea at Ofir, Portugal.

The following uses of energy language are suggested for modelling the sea:

(1) Analyzing models for comparative consideration of mechanisms. Some mechanisms in one field are recognized by those in another as familiar when they translate.

(2) Combining kinetics, dynamics, energetics, material balance, and economics in one method rather than writing separate equations.

(3) Combining the varied languages of several fields into one common language.

(4) Helping to insure that constraints of energy laws are included. This is done in the calculation of energy balance at each intersection or pathway.

(5) Providing a ready way to recognize emergent mechanisms resulting from combining units. For example, Michaelis-Menten effects emerge whenever a limited flow enters a multiplier.

(6) Providing a recognizable translation between the formulations of mathematics and science and the systems diagrams of Forrester, Koenig, and Payntor.

(7) Presenting differential, difference, logic, and integral equations in a form more readily carried in the mind in single unified form.

(8) Showing complex interactions for purposes of summarizing the impact of proposed environmental actions.

(9) Providing a ready way to portray average data in steady-state flows for purposes of computing missing data. Numbers placed on diagrams indicate visually the magnitudes of time constants, relative importance of flows, and the basis of coefficients in data.

(10) Providing the pathways for which total energy flows are calculated for energy cost benefit evaluations. The relative value of a pathway is taken to be the energy flow which it causes.

(11) When diagrams are provided with computer names and addresses (analog or digital), the diagrams facilitate debugging of simulation programs.

(12) Programming of complex systems in great detail may be followed by successive redrawing with compartmentalization (aggregation) to develop simple models with some of the essence of all classes of components, while retaining the overall integrity of material and energy balance.

(13) The diagrams help to prevent the unintended double insertion of a mathematical term. For example, a Michaelis-Menten relationship may be desired in the model and it is added. Yet the network into which it is added may already have this relationship in the configuration of limited flows reaching multipliers. Thus the modeller adds it twice unknowingly. There may be no harm in this if the system has two. However, hardware is economized and cost is saved by not duplicating unnecessarily those units that are at a micro-level of organization, where inclusion will not change performances much.

(14) Comparison of a great variety of marine ecosystems suggests a pattern of structure, function, and processes common to all systems that endure. The pattern is, as in Fig. 6.4A, one of obligatory storage and development of high-quality energy and information which is fed back to a controlling, pumping improvement of the energy-gathering processes.

Given in Fig. 6.4B is a very simple generalized structure for overall models of marine ecosystems which have some of each kind of subsystem. It is an elaboration of the "reward loop" pattern in Fig. 6.4A. The total generation of power flow is maximized by generating structure, energy, storages, information, and culture from which are fed back forces and amplifiers to pump in the maximum possible energy using all of the potential energy gained towards this. The criterion of competitive continuation and survival is the effective use of structures towards maintaining the energy basis.

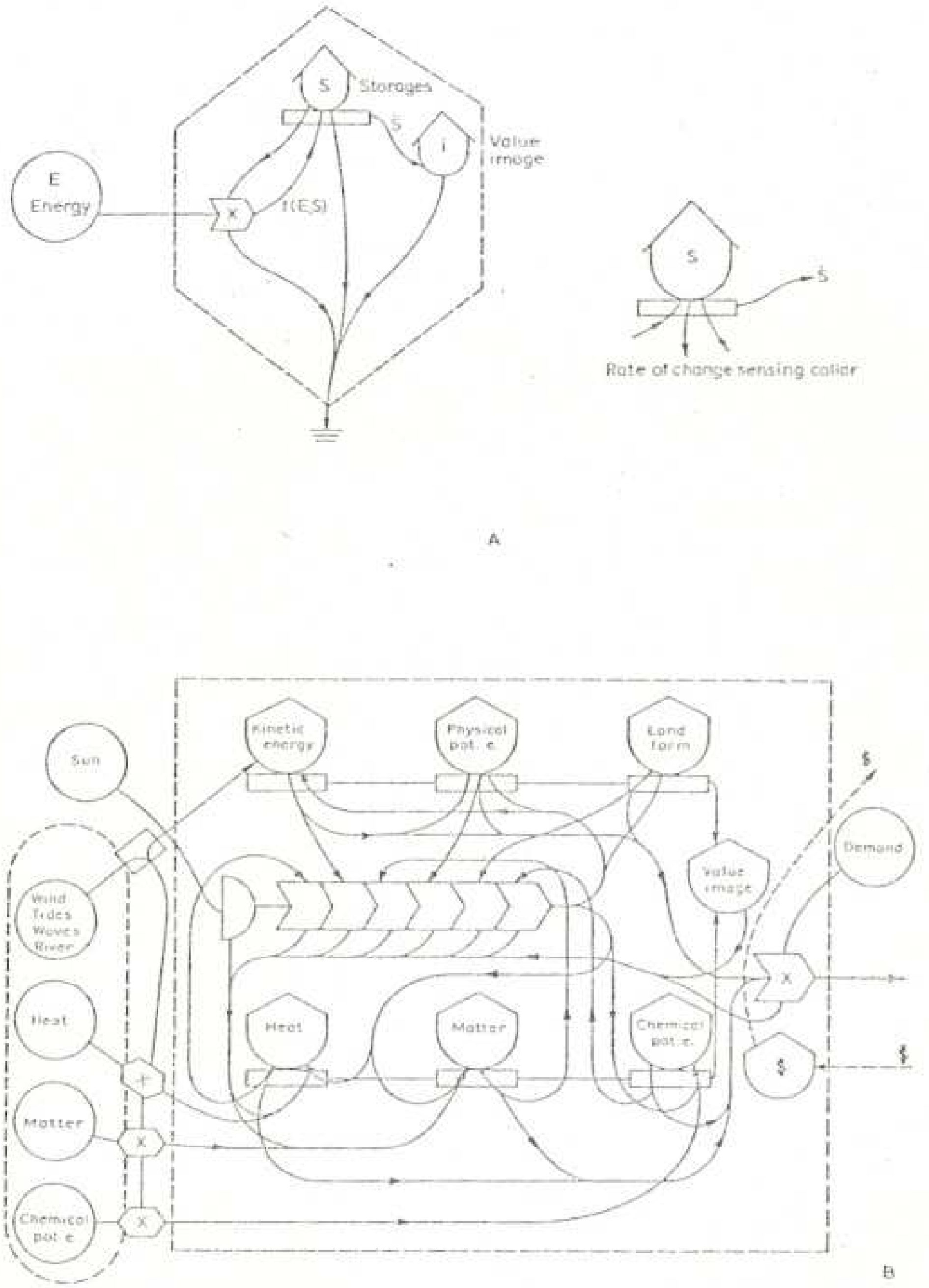


Fig. 6.4. General form of surviving systems with reward-loop feedback required for Lotka's principle of maximizing power with feedback from stored information, structure, and storages. A. Concept. B. Compartmentalized by physical, chemical, biologic, geologic, and economic sections. Value image *i* is generated in human interfaces as the sum of the rates of change of all energy storages, *Ṡ*.

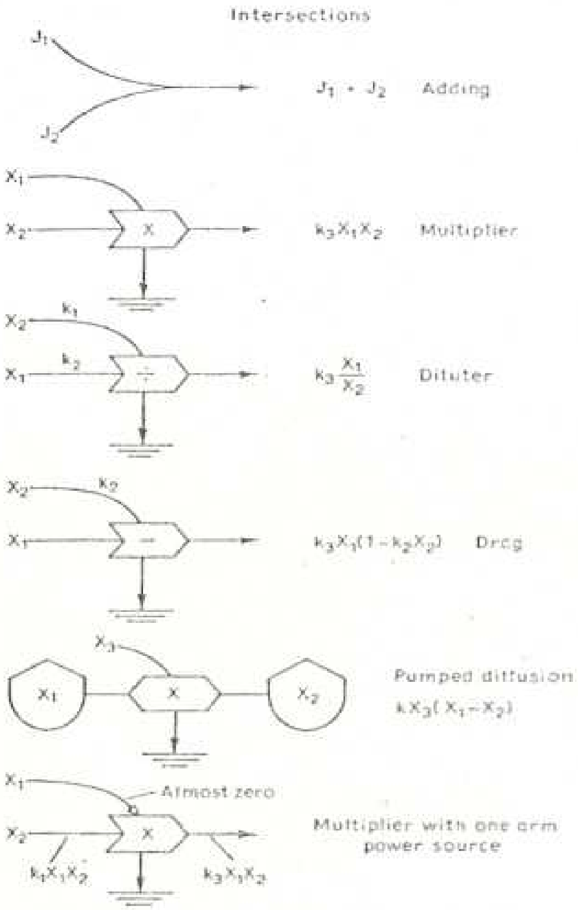


Fig. 6.5. Diagrams of common interactional relationships in energy circuit language.

(15) Diagramming as a common language may prevent the unnecessary duplicate development of the same concepts in different fields. For example, the kinetics of solar cells, chloroplasts, photochemical reactions, and some examples of diminishing returns in economics are all identical with the original enzyme substrate recycling model of Michaelis Menten in 1913. (See Fig. 6.5.)

(16) Diagramming in network form shows that many models, which have similar form in algebra or differential equation form, are entirely different phenomena, and this shows in network drawing. For example, many workers in biological oceanography call the limiting-factor action of external nutrients Michaelis-Menten, although the action is not a recycle. Monod, Rashevsky, and Lineweaver-Burke and Kira are the alternative antecedents.

(17) Diagramming with a group gathered around a blackboard has been

found useful in drawing out from several persons their combined knowledge.

(18) Diagramming of systems that are the focus of semantic argument often clarifies issues and meaning. The diagrams of limiting factor kinetics given in this chapter may be an example.

(19) For learning and teaching the diagrams may help in visualizing the various relationships in the environment. For example, chemists and biologists used to working with models in energy circuit language may learn physical oceanography without the mental divisions that comes from changing languages.

6.3. INTERACTION KINETICS

Because much attention has been given to the interactions of nutrients and light in photosynthesis and because there was focus on alternative models for this at the conference, we diagram the alternatives attempting to show the several ways of simplifying the real world system. The discussion considers various uses of the multiplier module related to limiting factors. Included are those equations given by Dugdale in his conference review of some recent approaches. See also previous presentations (Odum, 1971, 1972).

In Fig. 6.6 we remind the reader that chemical reactions or other interactions that require amounts of two entities, flow to the vicinity of the reaction to supply effective concentrations. If the two reactants are supplied with sources that hold concentrations constant, then reactions go as the product. Examples may be found in physics, chemistry, biology, geology, economics and many other fields.

In Fig. 6.6C we let one source (*S*) remain unlimited, but supply the second (*N*) at a constant rate of flow to the vicinity of the reaction. Now an increase of *S* will produce a limiting-factor hyperbola such as was so much discussed by Kira et al. (Shinozaki and Kira, 1956). If a steady state is achieved, a formula is obtained as given by Monod (1942) which looks like the one developed by Michaelis Menten. Many variations result when there are other inflows and outflows to compartment *N*.

If both sources are inflowing at constant flow, more complex formulae result as given by Rashevsky (see previous discussion, Odum, 1972).

Fig. 6.6B shows the enzyme substrate reaction of Michaelis Menten which also involves a limit to inflow on one side of the multiplier, but here it is limited by recycle because there is a constant quantity of recycling, reused reactant. This network is entirely different from the external limiting pattern in Fig. 6.6C, but at steady state the formula is quite similar. Notice that the system involves a multiplier, plus two sites of storage. The diagramming may

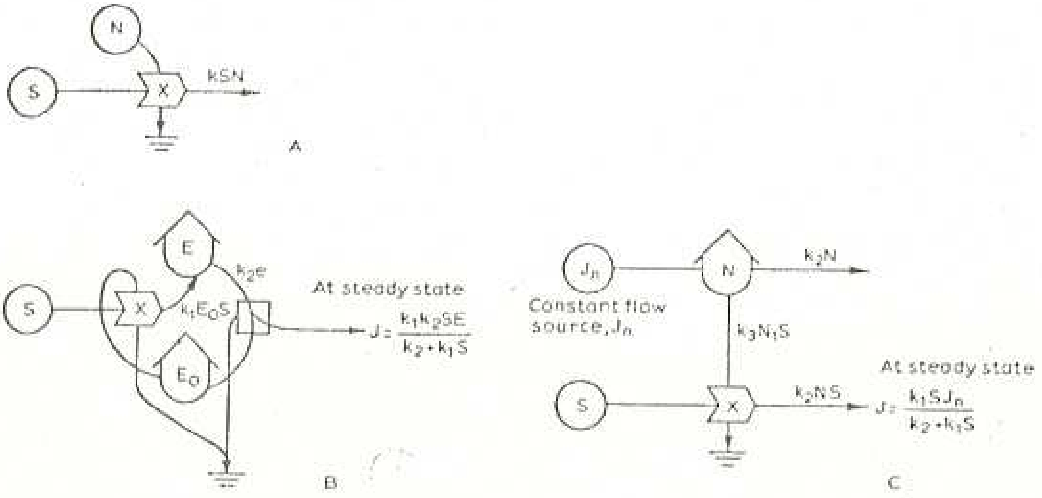


Fig. 6.6. Contrast of internal and external limiting-factor actions both of which have multipliers interactions. A. Unlimited supply. B. Internal recycle limit. C. External supply limit.

help those using hyperbolic equations to realize that their models can be used for the whole ecosystem when materials are recycling and constrained as in microcosms. In that instance the recycling material is nutrients, and the source of main energy is light.

The model has also been used for the initial chlorophyll reaction (Lumry and Rieske, 1959) and for inorganic solar cells (Billig and Plessner, 1949). Here the recycling material is a change in semiconductor state from receptive state to activated one that has charged holes with electrons eliminated.

Since an ecosystem has mineral cycles, contains hundreds of Michaelis-Menten enzyme loops, and starts with the clorophyll action, the ecosystem has Michaelis-Menten loops within loops within loops plus limiting-factor actions of the type in Fig. 6.6B, whenever there are outside sources limiting.

The question facing the modeller is "How many shall I add when only one may be enough to give the model a limiting-factor-type response?" Another question is "Do I recognize a limiting-factor action in my model or do I add a mathematical term, thus adding it twice without knowing it?" If an investigator has phytoplankton in bottles for measurement of limiting-factor kinetics, to how many nested limited reactions is he addressing his measurement efforts? See Fig. 6.7 for a system that has one each of four limiting-factor components in plants.

Another special limiting-factor action is the situation in some oligotrophic phytoplankton which have nutrient pumps that work to collect nutrients actively with feedback from burdened energy reserves. Here one has a Michaelis-Menten internal cycle-pumping inflow from an external compartment which may be externally limited as well.

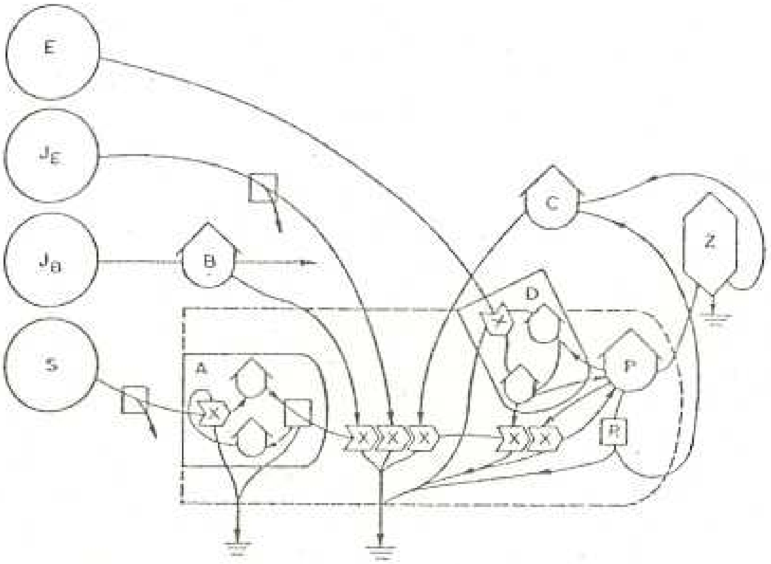


Fig. 6.7. A model of photosynthetic production that has five linked limiting factors operating simultaneously. A = chloroplast with internal recycle limit, B = external limit supply to nutrient B; C = recycle limits in external waters through larger ecosystem; D = limiting action of dark-binding membrane pumps found in some oligotrophic phytoplankton; E = externally limited supply.

Whereas a model with a single recycle arrangement for simulating limiting factors may serve to simulate the nested complexity of many, the coefficients can hardly be identified with the coefficients of any one of the many limiting-factor systems that could be isolated in physiological work. Here one may defeat the purpose of ecological modelling if one tries to identify physiological coefficients with that at the more complex ecological level of aggregated organization.

Consider two ways of getting coefficients after a model is decided upon. In one the organisms are isolated and experiments run on the effects of the interacting inputs. Enclosure changes the system so that the values are not those of the system. Another way is to take observations in the field of the interacting variables and devise ways of estimating rates *in ecos* (in the operating ecosystem). The coefficient is then the only unknown in the equation for that interaction.

Another limiting action which is diagrammed frequently, is the situation when there is a pumped (multiplicative) drain pulling on a flow that is independently determined. In Fig. 6.8 this situation shows the pumped flow taking part of the flow, capable of pulling up to, but not quite all of, the inflow. There are no appreciable storages in this action so that there is always a limiting hyperbolic kinetics. Actually no force may be delivered without a small storage, and the action of a flow in promoting another flow

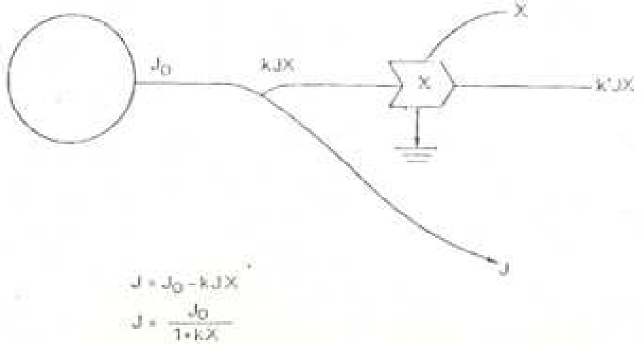


Fig. 6.8. Limiting-factor situation when a multiplier demand, JX, operates from a controlled flow rate, J_0, and local storages are negligible.

does have small storages, but the diagram and algebra in Fig. 6.8 is for the common instance that the storage is too tiny to affect rate responses in the time scale of interest.

Another mechanism being used in some marine models is a multiplicative demand in proportion to that concentration in excess of a threshold with no negative flow. An energy circuit translation of the algebraic expressions is given in Fig. 6.9A and 6.9B. Again the question may be raised whether to add a limit feature or let the system generate its own. Fig. 6.9C has no special threshold feature but will yield no net increase, except when energy input is enough to pay for energy costs of maintaining storage (k_3F). Adding the threshold mechanism over and beyond the inherent minimum for growth (Fig. 6.9D) might be appropriate if the organisms (2) had a behavior mechanism for stopping the feeding work and if the fine detail of the performance were desired.

Another algebraic expression used to indicate a limiting action on an inflow is the exponential expression diagrammed in Fig. 6.9E referred to in some papers as Ivlev's equation (1961), or where light is concerned, the Mitscherlich equation (Verduin, 1964). Whereas the shape of the effect of increasing action on flow is asymptotic, resembling the hyperbolic actions, it differs in being independent of limiting flows (recycle or outside limiting type). The asymptotic property is not subject to the other variables. What the exponential means in terms of mechanism may not be clearly stated.

6.4. PHYSICAL COMPONENTS IN ENERGY LANGUAGE

Whether diagrammed for explanation purposes or for macroview simulation, marine models would be very incomplete without the main physical flows, forces, and storages. In Fig. 6.10–6.17 an attempt is made to translate

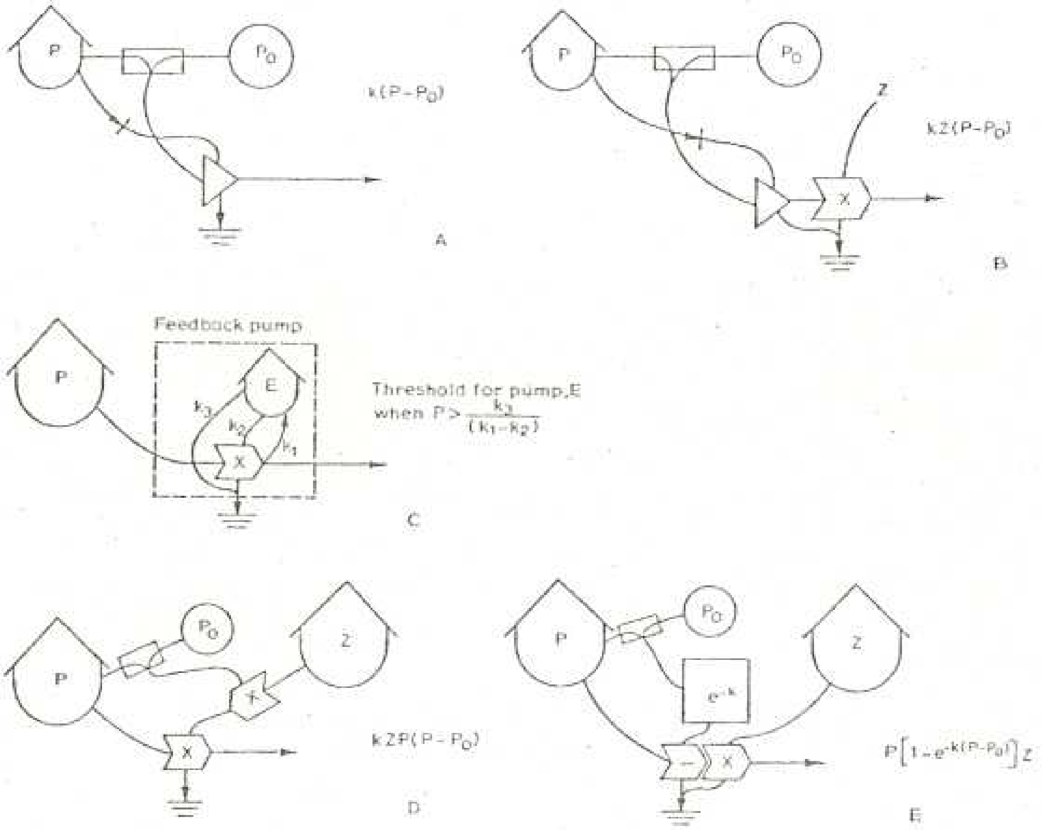


Fig. 6.9. Configurations of energy intake which have thresholds below which there is no growth of rate (see also Figs. 6.6—6.8). A. Linear supply. B. Threshold active demand (multiplier). C. Pseudo-logistic growth; threshold for energy pumping for achieving net growth. D. Threshold control of energy pumping. E. Exponential drag.

the main modules and configurations of the equations of motion into energy languages, the pathways being lines of force balance.

Characteristic of these components are pressure-generating energy storages, energies stored as kinetic energy of velocities, and inertial forces whenever there are accelerations. A storage of a fluid has a pressure in proportion to its quantity Q and its packaging coefficient C (see Fig. 6.10). A force from a pressure potential may generate a velocity and transfer kinetic energy to the motion which may be rotational or translational. Kinetic to potential energy changes and back do not require heat sinks. Kinetic energy is stored relative to the coordinates of the model. When translational velocity exists it has a direction that must be indicated on the diagram. If absent, its direction is taken as into the paper, perpendicular to pathways shown on the paper.

In Fig. 6.10A is shown an arrangement that generates a pressure gradient

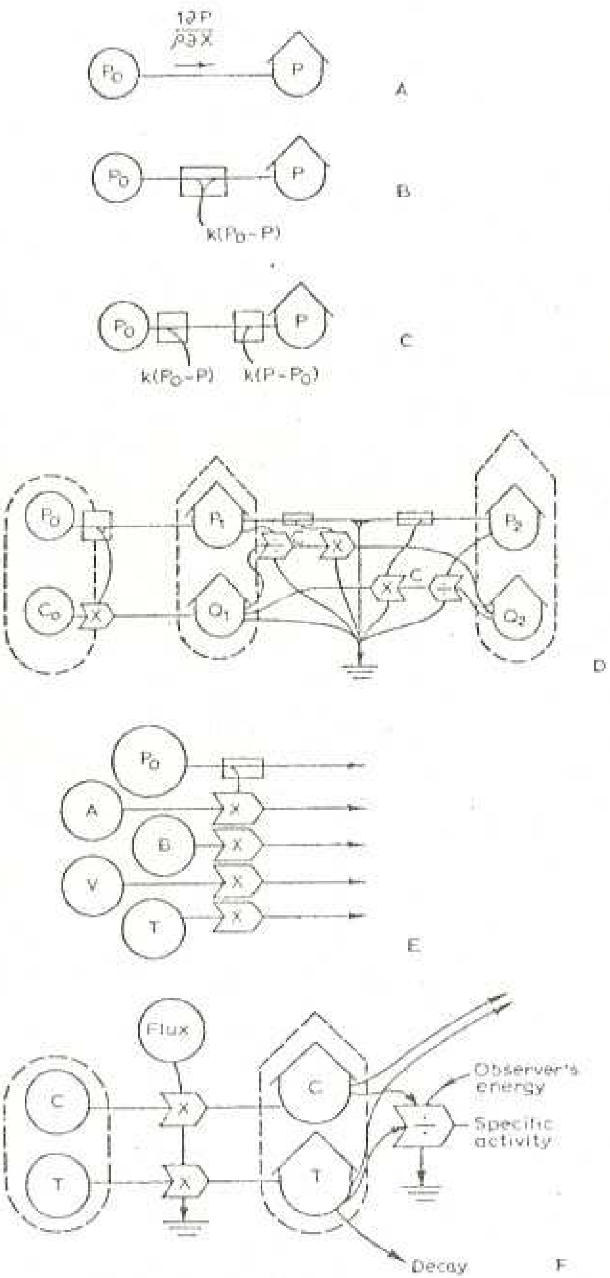


Fig. 6.10. Flows of several types driven by pressure gradient force which is transporting other quantities by advection. A. Pressure gradient force from an outside forcing function exceeding backforce from internal storage. B. Pressure difference sensor; force in proportion to flux-deriving energy from the flux. C. Two flux sensors, one sensing flow from left and one from right, both flows are proportional to pressure gradient. D. Pumped transport of a chemical by pressure gradients. Note state variable is total quantity Q, and ratio to fluid quantity P is concentration. E. One-way advection; transport of chemical quantities, momentum, and heat as in a river inflow. F. Radioactive traces with its carrier.

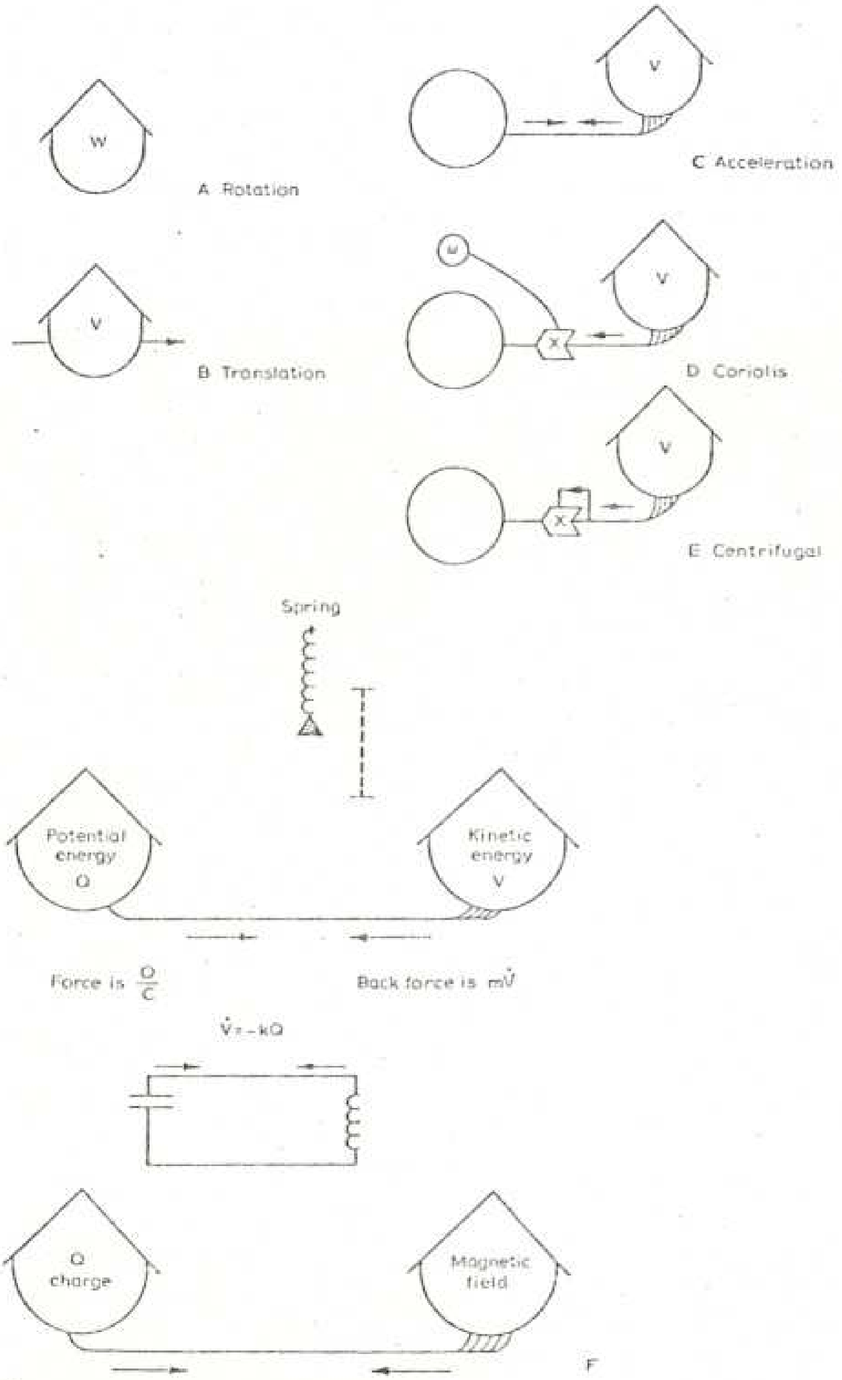


Fig. 6.11. Representations of momentum, kinetic energy, acceleration, and inertial backforce. A. Storage of rotary. B. Translational momentum with accompanying kinetic energies; note vector indication of translational momentum. C. Symbols for acceleration and inertial backforce. D. Symbol for Coriolis-acceleration inertial backforce. E. Symbol for centrifugal inertial backforce. F. Oscillator with potential and kinetic energy.

force according to the difference in pressure. Direction from outside is indicated in Fig. 6.10B as from a river. The flow of fluid is proportional to the difference in pressure. If the advection is tidal, flow is possible in either direction and in that case no barb is used for the pathway. In proportion to the flow of fluid, constituents are transferred as the product of concentration and flux with a string of four multipliers that draw their transport from the fluid. Transport includes chemical stuffs A and B, momentum, and heat.

In Fig. 6.11A, kinetic energy is indicated by storage units in which the state variable that carries the energy is either velocity or angular velocity.

Fig. 6.11C shows a convention used where acceleration is generating new kinetic energy against inertial forces that oppose any acceleration according to Newtonian convention. Note the brush-like connection of pathway to tank chosen to indicate inertial energy transfer without heat sink.

Another kind of inertial force for those turning with the earth is that due to rotation of the earth's axis under a fluid velocity. The product of the earth's rotation and the velocity is indicated in Fig. 6.11D.

6.5. INERTIAL DISPLACEMENT OSCILLATOR

Oscillators are a favorite class of systems for studies and instruction in electronics, mechanics, and systems modelling. Vibrating springs, pendulums, oscillating seiches, sine waves, etc., are various examples. Given in Fig. 6.11E, in differential equation form and in energy circuit language, is the essence of a simple oscillator without dissipational elements. Acceleration is negative to the displacement according to one equation form of this. In energy terms there is a balance of inertial force and potential derived static force. The inertial backforce is proportional to acceleration and the driving force from the potential storage is proportional to the storage of the state variable that goes with displacement. Potential energy contained may be water or mass of the spring stored against gravity. Another example is the oscillation between electrical charge and backforce generated by surges of electric current that induce and store energy as magnetic field.

Molecular diffusion is indicated in Fig. 6.12, with energy for motion derived from the energy storages within the gradients, the energy emerging as dispersed heat in the heat sink. If there is a temperature and a chemical gradient, the two diffusions are coupled according to the Onsager theory as shown in Fig. 6.12B. In Fig. 6.12C parallel velocity flows exchange momentum through the transfer with molecules diffusing laterally.

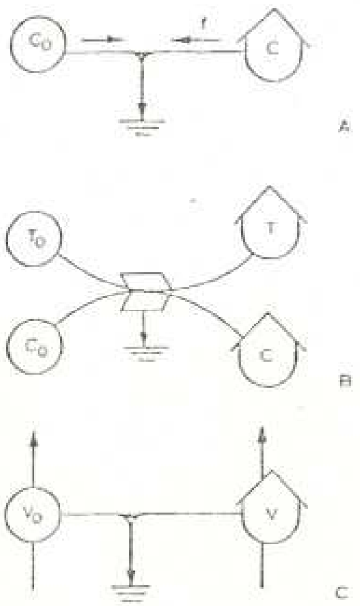
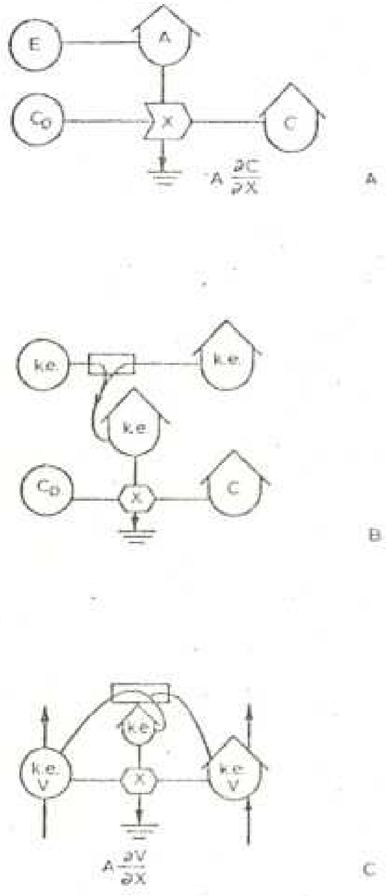


Fig. 6.12. Forms of molecular diffusion. A. Chemical diffusion. B. Thermal coupled chemical diffusion. C. Momentum diffusion.

6.6. ENERGY STORAGE, ENERGY QUALITY UPGRADING, REWARD LOOP PUMPING, AND EDDY DIFFUSION

From Lotka's principle of selection for maximum power comes the corollary that energy gradients with some amount of potential energy beyond a minimum threshold win out in competitive selection if they build potential-energy storages with enough quality to act as amplifiers on the upstream flows serving to pump and accelerate energy capture. Since any energy storage has an inherent rate of entropy increase because of its storage gradient relative to surroundings, there is a drain of potential energy. Since any energy flow generates random noise, it generates continual choice in configurations so that selection for maximum power can proceed rapidly to develop energy reward loops, and the more energy available, the faster the evolution and the stronger the feedback loop system developed. The feedback pumping loops (Fig. 6.4A) result in accelerated energy inflow when the energy gradient is sufficient to generate a storage in excess of its storage loss rate.

Eddy diffusion is a kinetic-energy storage in rotary motion that serves to feed back high-quality, upgraded, potential energy to pump in more, because the eddy acts like a wheel or ball bearing upon which the transport can flow



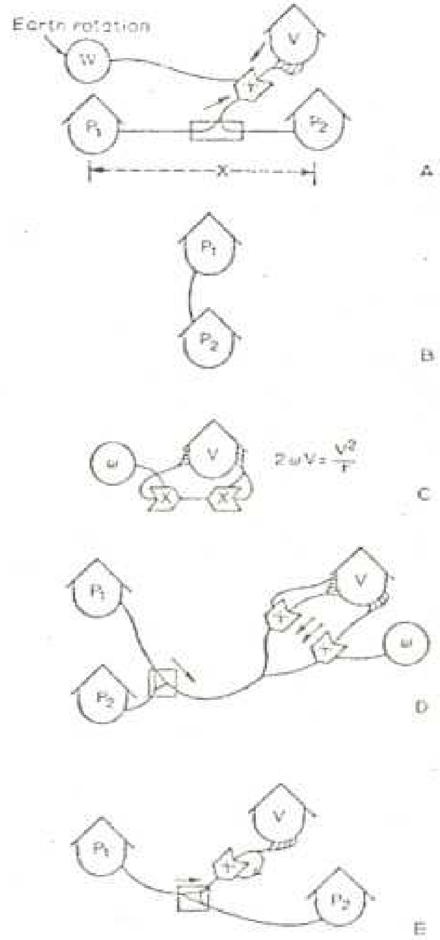


Fig. 6.13. Forms of eddy diffusion. A. Externally forced eddy diffusion of a chemical. B. Chemical diffusion pumped by coupled momentum gradient. C. Momentum diffusion with eddy self-generated. If not shown, velocity vectors are into the paper as in c and d.

Fig. 6.14. Common equilibria in physical oceanography and meteorology. A. Geostrophic balance. B. Hydrostatic balance. C. Inertial motion. D. Meander, gradient wind balance. E. Cyclostrophic motion.

faster than competing pathways. The double-pointed block is the symbol for simultaneous circular facilitation of flow in both directions at once. Recirculating transport carriers are driven by energy stored and maintained in the circular process (Fig. 6.13).

In the consideration of the physical networks of ocean and atmosphere, it is customary to recognize situations in which there are force balances between static forces from energy storage and inertial forces or between inertial backforces. Some common textbook examples are diagrammed in ener-

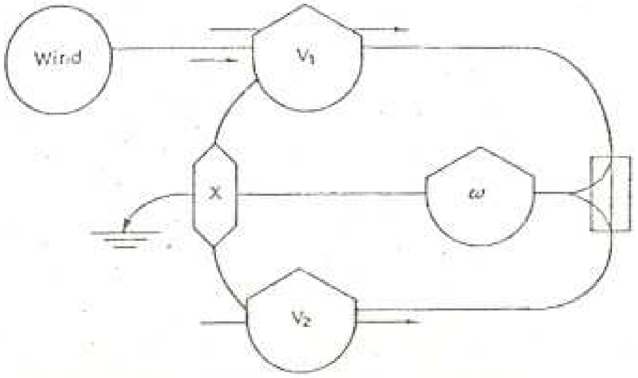
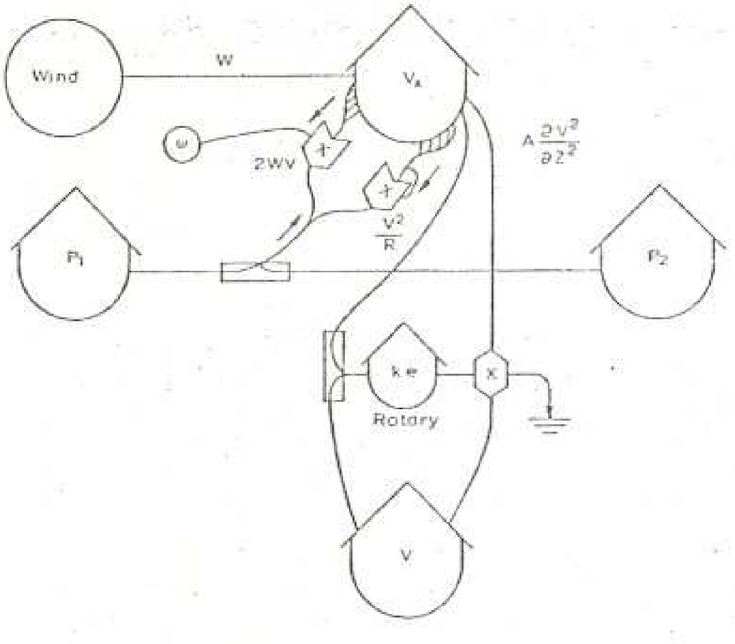


Fig. 6.15. Steady-state balance of wind and frictional force in one dimension (ω denotes eddy motion).

gese in Fig. 6.14. The energy circuit language helps to indicate the sites of energy storage and the force pathways at the same time. Fluid flow occurs along the pathways whenever the forces are imbalanced continuing until velocities change enough to reestablish the force balances. In the real world these systems cannot exist without some additional energy support to match



$$\frac{1}{\rho}\frac{\partial p}{\partial x} + 2\omega V \sin \theta + \frac{V^2}{r} + A\frac{\partial^2 V}{\partial z^2} + W = \frac{\partial V}{\partial t}$$

Fig. 6.16. Energetic circuit diagram of the equation of motion in one dimension with velocity directed into the paper perpendicular to axis of pressure gradient.

that lost into frictional, entropy-increasing, heat dispersion. However, in customary pedagogy, the energy supplements and sinks are not shown in Fig. 6.14. The force balance indicated in Fig. 6.15 is between the component of wind stress and vertical eddy friction opposing the fluid velocity in one dimension without horizontal or vertical terms. The various terms diagrammed in Fig. 6.11—6.15 are combined as a diagram of the equation of motion for one axis (Fig. 6.16).

6.7. FIELDS AND BOXES

The continuous fields of force affecting the fluids of atmosphere and oceans are often visualized in modelling as networks of discrete storages connected by pathways of force and flux, the size of the continuous fluid included in each being an arbitrary decision depending on the detail desired. The sea is thus visualized as a network of repeating duplicate unit models. At each node of the network of similar storages and connectors, there is a set of forces operating, and diagramming one such unit characteristically represents the whole system's operations, each node being similar qualitatively.

At this conference such unit models were referred to as box models. As given in Fig. 6.17A unit model boxes are shown in three-dimensional arrangement. At other times one box is made for the whole system (Fig. 6.17B) without dividing the area into nodes. Simplification in space by overall aggregation leaves some room in the model and computer capacity for complexity other than dissection of fine-grained spatial detail.

6.8. GESTALT IN PHYSICAL OCEANOGRAPHY

In Fig. 6.17C a two-dimensional diagram is given showing a unit model of eddy diffusion of salt (*C*). If this methodology of repeating connected duplicate submodels were applied to an organism, one would divide the organism into hundreds of grid points with unit models, rather than recognizing the natural divisions in the compartmentalizing of the model into head, heart, digestive system, etc.

Aggregation may have a deeper meaning beyond practical reasons for simplification. The action of natural selection by Lotka's principle of maximum power is not restricted to any size dimension, and the larger dimensions of the sea and atmosphere's motions may have self-organized building structures and motions on a larger scale for useful power maximization. If this is so, then the larger systems of the earth, the oceanic gyres, the cyclones, the general circulation, etc., may be regarded for modelling in the

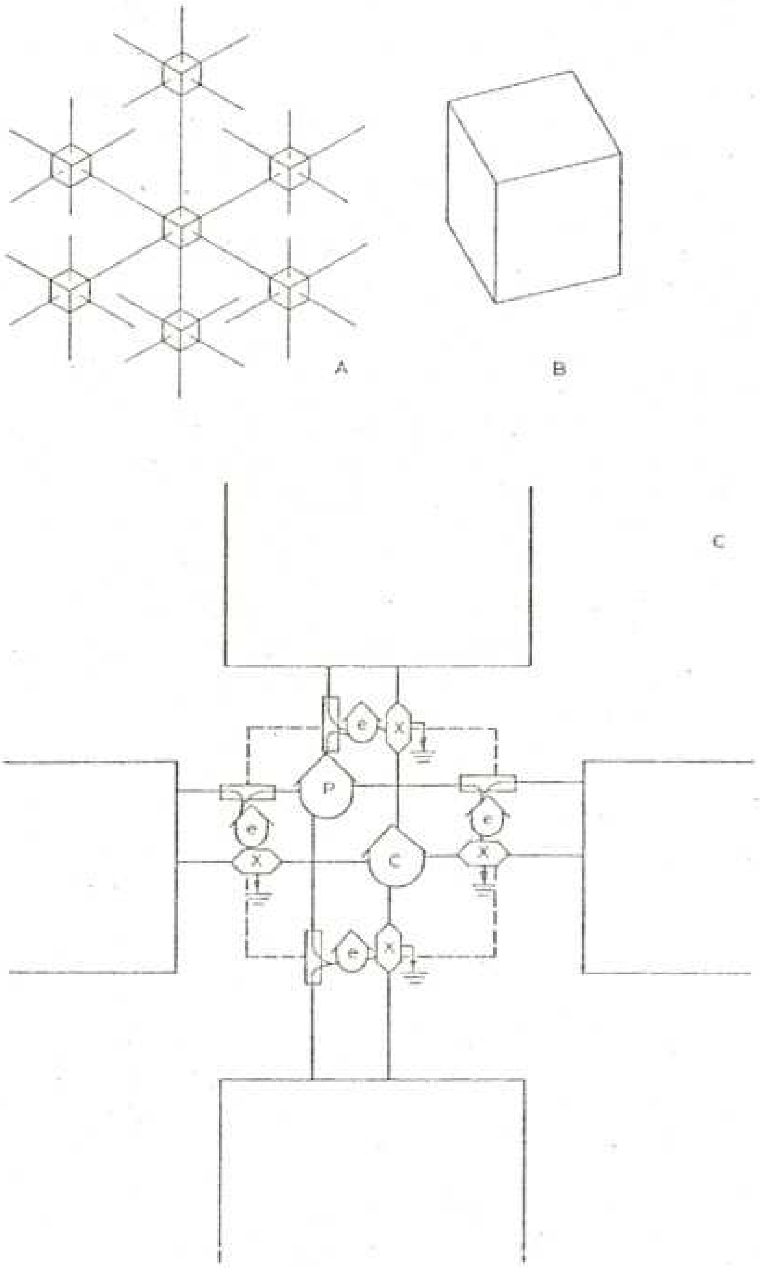


Fig. 6.17. Diagrams illustrating the alternative of modelling a system as one box with overall values for each. A. Model with a network of duplicate unit model boxes connected by pathways of forces, flows, and energies. B. Aggregated model using only one unit model for the overall systems. C. Example of the linking of each unit model to that in the next spacial segment. This example has diffusion of chemical stuffs *C* under the flows generated by pressure distribution *P* whose flows generate eddies.

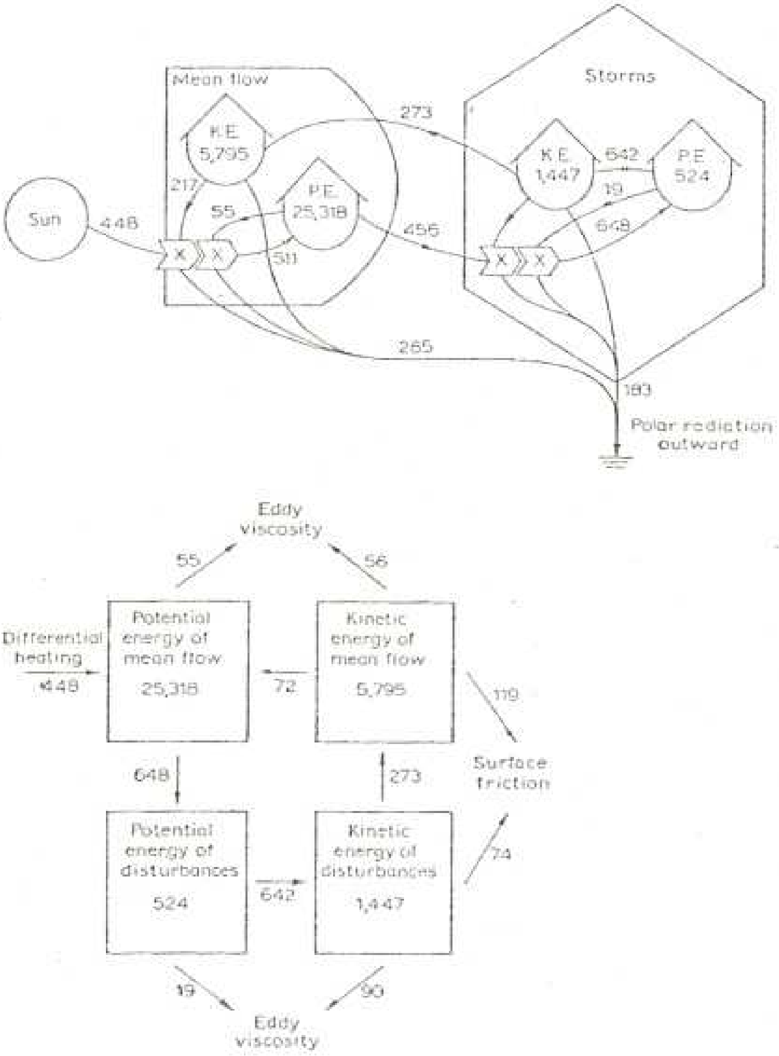


Fig. 6.18. Energy circuit translation (above) of a model of the earth's general circulation given by Hess (1959) (below) quoting Charney and Phillips (1953).

same way that a biologist considers an organism as the proper unit for model recognitions because of unity of organization of energies. Instead of breaking the system into hundreds of nodes calculating force balances and flows in enormous detail with expensive computer manipulations, the system is compartmentalized into only the few main categories of energy storage and flow with emphasis on the causal overall forcing functions, and main feedback mechanisms affecting structure. The trends in recent years to determine overall energy budgets for hurricanes, the earth's general circulation, etc., represent trends toward macro-modelling, although efforts at this kind of modelling in the sea seem few. In Fig. 6.18 an energy budget for the general circulation of the earth given by Hess (1959) from Phillips (in Hess, 1959, p. 347) is redrawn in energy circuit language adding the appropriate symbolism for the forces and feedbacks believed necessary. Note that the empirical study produced the same kind of general energy storages to input pumping as generalized for all systems in Fig. 6.4. This physical system resembles biological ones such as in Fig. 6.1 and 6.2.

Generalizing, one sees the structure of the earth's sea bottoms and shores as built by the energy actions. These forms serve as quality upgraded potential energy, information, and material storages that feed back control actions on the energy input processes. Geomorphological form and information as measured by capital energy investment becomes as much a state variable as biomass in biology or water in hydrology.

In trying to persuade those who work on mechanistic details that there is an overall energy plan in all surviving systems, it is sometimes useful to mention the beach as an example of the potential-energy storage of a system, that builds that physical structure for capturing and channeling further energy toward a stable continuing regime, one adapting to seasonal surges.

In overall macro-modelling and diagramming of physical systems, one questions the usefulness of commonly used catch-all phrase "boundary conditions" referring to various connecting terms in a field of submodels. When one makes energy diagrams, one is forced to distinguish clearly between outside, energy-driven, forcing functions, internal storage state variables, and energy sinks some of which may be energy pumped from outside work actions. Effects of geomorphology become either energy sources if external or storage if internal. The energy diagrams keep the forces and energy considerations under simultaneous consideration rather than as two separate systems.

6.9. POTENTIAL ENERGY BUDGETS FOR PERSPECTIVES; ENERGY QUALITY

Perspective on the importance of components to a system may be gained from energies controlled. Energy diagramming provides a means for converting potential energies in various parts of a system to a common currency often though there are different degrees of energy quality to be recognized. There are two energy values to a flow, one that it carries by itself as its sole energy value as if it is a sole source. The second value is the energy flow that it releases when it reacts at an energy intersection with a second energy source. A high-quality energy has a high ratio of energy released to energy contributed, and this ratio may serve as a quality of energy measure. In

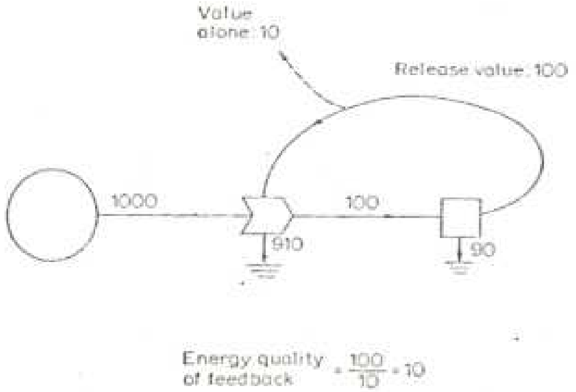


Fig. 6.19. Diagram illustrating energy-quality ratio as the ratio of two energy values that characterize interacting energy pathways.

effect the upgraded high-quality energies are attributed energy values in terms of the amounts of energy of lower quality it can control. For example, in Fig. 6.19 the energy quality of the feedback is 10 kcal (kilocalorie). It is this second value that is useful for impact considerations.

An examination of potential energy in the sea produces some surprises. Given in Table 6.1 is a comparison of the potential-energy inputs to an estuary from physical, biological, chemical, and geological inputs. Solar energy is not potential energy on the same scale as the other high-quality energies until its costs of concentration is included. The fraction of heat from the insolation absorbed, that is potential energy, depends on the Carnot ratio ($\Delta T/T$) where ΔT is the heat gradient generated. Energy involved in evaporation is mostly reversible energy and not potential energy. Although many people visualize physical energies as large enough to dominate the biological, chemical, and geological aspects this may be a misconception. There is as

TABLE 6.1

Energy inflows to Crystal River Estuary on West Coast of Florida*1

Energy flow	kcal per m^2 per day
Tidal energy absorbed	0.08
Wave energy absorbed	2.5
Solar energy in photosynthesis	28.0
Solar energy in heating, 2°	27.0*2
Chemical potential energy in freshwater inflow diluting	66.0

*1 Calculations from Odum, H.T., 1974. Energy cost benefit models for evaluating thermal plumes. Thermal Ecology Symposium Proceedings, Division of Technical Information, U.S. Atomic Energy Commission, Oak Ridge, Tenn. (in press).

*2 Heat flow times Carnot ratio.

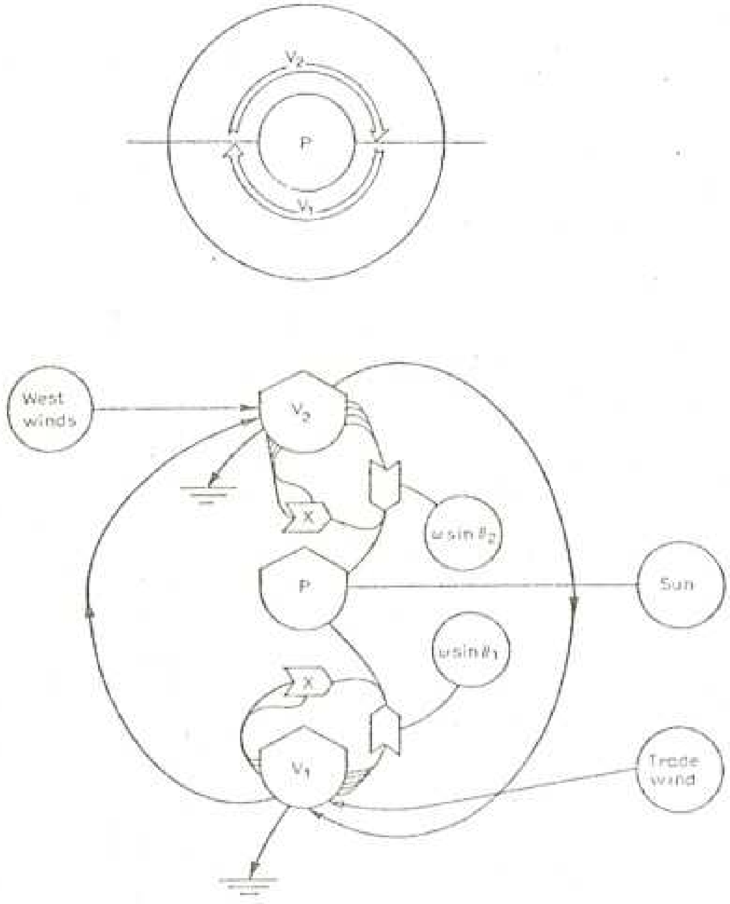


Fig. 6.20. Macroscopic mini-model for an oceanic gyre and simulation of that model.

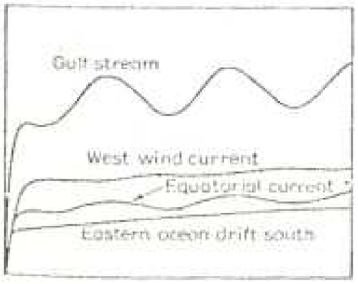


Fig. 6.21. Simulation of model in Fig. 6.20 with sinusoidal inflow program for seasonal winds and heatings. V_2 is West wind current and V_1 Equatorial current.

much potential energy involved in these latter as in the sea's and atmosphere's physical world. The ability of biological and chemical processes to generate controls over physical processes may be greater than often realized. Modelling physical systems without the high storage energy controls of the rest of the system is likely to be erroneous.

6.10. ENERGY COST-BENEFIT CALCULATIONS AND IMPACT STATEMENTS

For considerations of value, estimates of high-quality potential energy flow were suggested since the ultimate purpose of any system is later judged by the survivor as good if it was part of survival. Contributions to maximum power and survival thus are measures of value for purposes of maximizing one's economy and ability to compete. Energy diagrams indicate the interactions of factors recognized in proposed environmental changes, and the energies involved served as a measure of relative value. Since the energies involved in many parts of the marine systems are of similar order of magnitude, planning for change in coasts and estuaries that is based on physical properties only may omit consideration of most of the pathways affecting overall value and system survival. It may be incorrect to do piecemeal and subsystem models where they are organized to maximize all the combined energies in coupled and interlaced networks. Approaches to the environmental field made by separate disciplines may show mechanisms but cannot yield plans or predictability if the pattern that survives depends on the whole unified energy maximization.

6.11. A MACROSCOPIC MINI-MODEL SIMULATION*

To illustrate the approach of macroscopic mini-models, a simplified network model for an ocean gyre is given in Fig. 6.20 with forcing functions from sun and wind. In Fig. 6.21 are some simulation graphs from manipulation of forcing functions in seasonal variation. The system generates a rapid current of Gulf Stream type on the left pathway.

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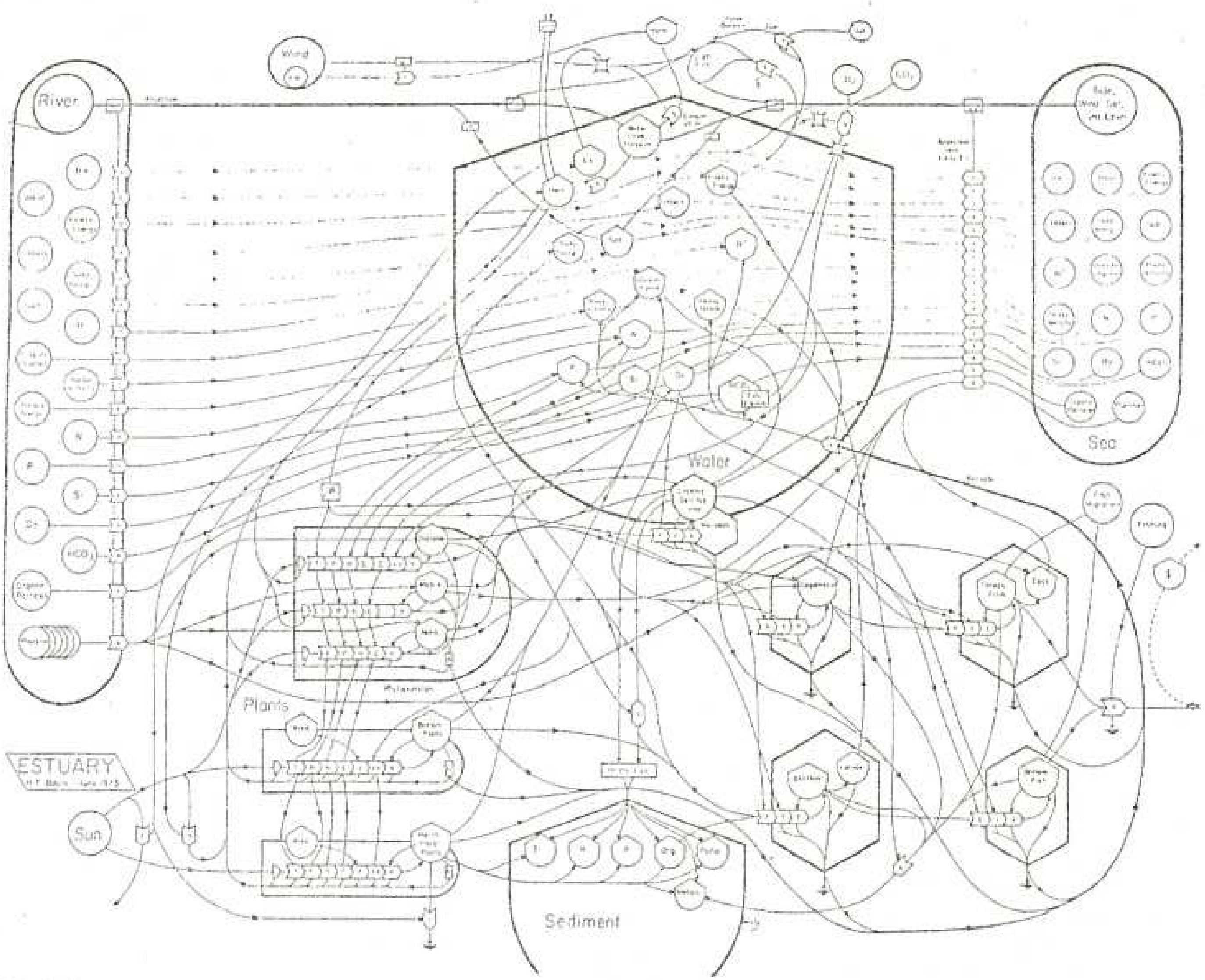

Model for an estuarine system translated into energy circuit language.