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Process-response systems in physical geography

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Werner H. Terjung

with 12 figures

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Foreword

Geographers investigating the physical landscape do not always need to solve a problem from its very roots or conduct extensive programs of field data collection in search of relationships or extant processes. He or she should be aware of a set of basic principles, applicable to most research problems in physical geography.

A plea is made to broaden the research and teaching in physical geography by the inclusion of process-response modeling. Such an increased deterministic orientation derives much of its basic principles from the application of the First Law of Thermodynamics and NEWTON's Second Law. The numerical modeling of physical process-response systems eventually should include socioeconomic decision-making systems, thus making physical geography of greater relevance to the cultural-economic aspects of our discipline and to mankind in general.

This work was partially funded by a grant from the University of California. I very much thank the producers of Colloquium Geographicum for their interest in my work and for the opportunity extended to me to be published in this series. I gratefully acknowledge the valuable comments of JIM BURT and JOHN HAYES. My greatest debt is to the late STELLA LOUIE, and PATRICIA O'ROURKE, who, in addition to in-depth discussions, were instrumental in the successful teaching of the basic principles of process-response systems in physical geography to groups of freshmen at the University of California, Los Angeles.

Los Angeles, in summer 1981

Werner H. Terjung

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I. Basic Theory

Since at least the 17th century, when VARENIUS subdivided our discipline into its general (universal) and special (regional) aspects, geography has continued to contain a double focus on the physical and the cultural sciences. During modern times this dual approach increasingly has become a problem because of the difficulty of a continuing dialogue between physical and human geographers. Communication is at an all-time low, even within physical geography. The reason for this growing schism, which is threatening to tear asunder the unity of geography, is the increasing complexity of the rapidly developing social and physical sciences. To be a "general geographer" who is still capable of communicating effectively with the various subfields (and their associated systematic disciplines) of our discipline has become difficult. The days of the "renaissance man" are long since gone. This generalization is especially applicable to physical geography.

However, man lives in one world and geography attempts to study that unity. Man is part of a total environment which is part of a gigantic system, powered by the solar energy cascade and the tectonic energy cascade. If geography is to provide a link and integration between the social sciences and the physical-environmental sciences, a systems analytical framework has to be adopted which emphasizes the spatial results of such system processes in regard to man and his works. The importance of such an intermediate position becomes even more pressing in light of the accelerating schism between the physical and social sciences and the increasing alienation between the public and science in general. Research and, equally important, the teaching of geography should be directed toward the bridging of such ominous gaps.

Introduction

Many geographers are tilling the fields of physical geography with little or only spurious concern for the imprint man is leaving on this planet. True, the difficulties and complexities of a more relevant treatment are stunning. Yet, this vast physical system is a unified system where a change in any element of the landscape entails a change in all of the remaining elements. The science of geography, as opposed to catalogues of facts, could also be a system of ideas instead of a purely automatic revelation of the "realities" of the world dependent on amassing field data. The complexity and the continuity of the real world demand a unified approach where reality could be considered a hierarchy of organized, interlocked systems which can be identified at all scales of magnitude and all degrees of complexity.

This paper addresses itself to two basic goals: it is attempting to alert geographers to consider supplementary research efforts, methodologies, and philosophies as compared to current viewpoints; and it attempts to show an additional way of approaching the teaching of the physical aspects of geography. I am not addressing myself to the practicing, specialized researcher; to him this presentation may appear crude and incomplete. My main objective is to gain the attention of the general geographer.

At this point the paper can be construed to be more a vision than a true blueprint. The presented ideas are not suggesting a replacement, but should be viewed as an addition to the existing body of physical geography. Only the most recent literature (excepting geodynamic, weathering and social systems) has been casually surveyed and no claim of an extensive review is made. It is inevitable that much important work has been overlooked. To present a substantive review of even the last few years is beyond the scope of this paper.

Systems in Physical Geography

In my view, one of the aims of physical geography could be the examination of the responses of the landscape envelope to inputs of energy, mass, and momentum (Fig. 1).[1] Landscapes are open systems, that is, energy, mass, and mo-

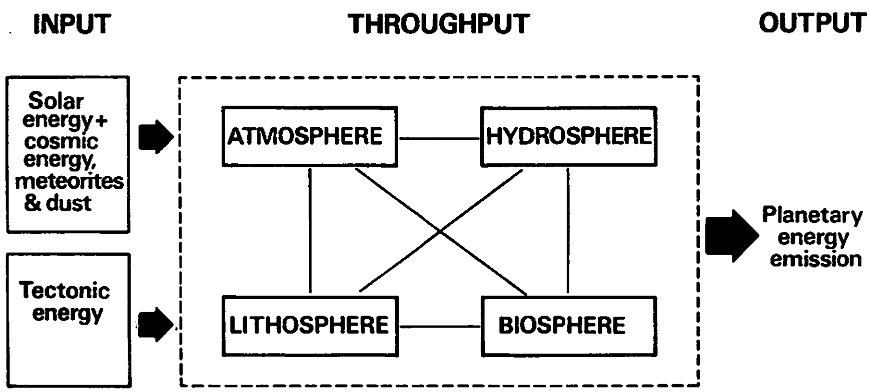


Fig. 1: Subsystems of the earth-atmosphere system connected by energy, mass, and momentum flows.

mentum can be freely exchanged across boundaries. Frequently a system's components and interrelations tend to become adjusted so that a steady input results in an approximately equal output. This situation tends to be self-regulating and operates to create a steady state, in contrast to a transient stage.

For instance, let us examine the rather trivial example of an arbitrary system located somewhere along the slope of a drainage basin (Fig. 2). This "system" has inputs of energy (e.g., solar radiation, atmospheric and terrain longwave radiation, conduction, convection, advection, kinetic energy from fluvial action and falling precipitation, etc.), mass (e.g., debris, chemical and organic materials, water, precipitation, air moisture, etc.), and momentum (the motions of

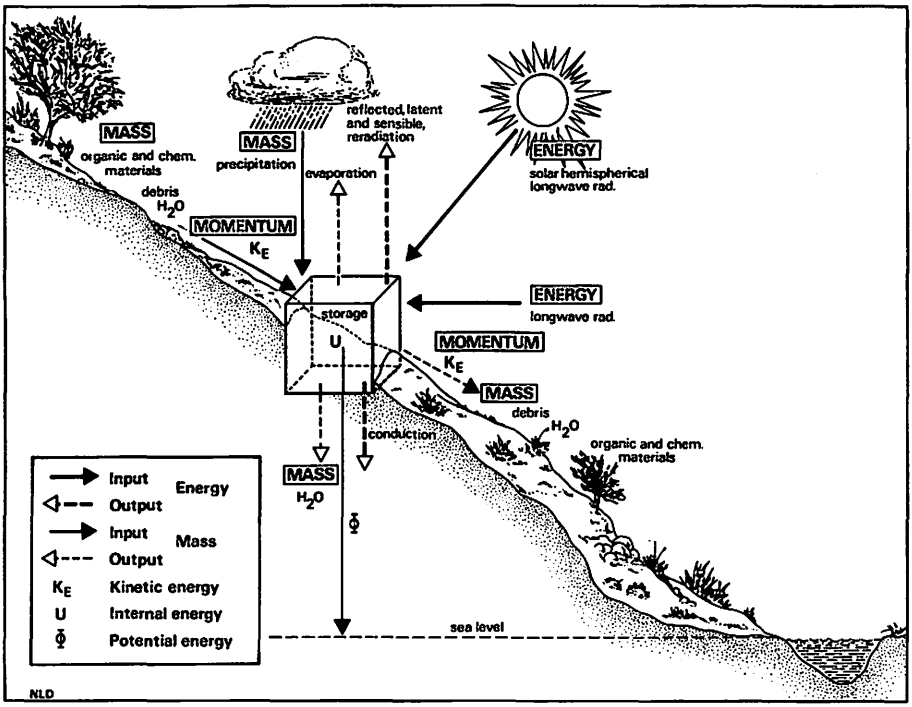


Fig. 2: An arbitrary "system" on a section of slope. The term sea level can also be interpreted as base level.

the various masses). By virtue of its elevational position (z-axis) this system has a characteristic potential energy which is inversely related to the entropy of this slope section. This potential energy can be changed not only by denudation, but also by tectonic uplifts. Outputs of energy are in the form of reflected solar radiation, infrared reradiation, sensible and latent heat fluxes, conduction, and kinetic energy. Mass can be disposed by the continued downslope movement of debris and by water seepage and evaporation, whereas momentum is exported via such mass movements. A steady state is achieved when there is no increase or decrease in "storage" of energy, mass, and momentum. For instance, a steady state for energy results when the internal energy $\underline{U}$ of the system does not change in time, i.e.,

$$\frac{T_1 - T_2}{t_1 - t_2} = \frac{\Delta T}{\Delta t} = \frac{dT}{dt} = 0, \tag{1}$$

where $\underline{T}_1$ and $\underline{T}_2$ are the temperatures (caused by the internal energy $\underline{U}$) of the element at times $\underline{t}_1$ and $\underline{t}_2$. More generally, a steady state exists when

$$\frac{d(\text{energy})}{dt} = 0; \quad \frac{d(\text{mass})}{dt} = 0; \quad \text{and} \quad \frac{d(\text{momentum})}{dt} = 0, \tag{2}$$

or when any combination thereof equals zero. Transient conditions (e.g., $dT/dt \neq 0$) are characterized by increases or decreases of storages. Theoretically, the prediction or simulation of the various possible states occurring inside this physical process-response system can be accomplished by "numerical modeling" (for instance, the simultaneous numerical solution of combinations of the equations of motion, kinetic energy, radiative transfer, water vapor, internal energy, state, continuity, and the hydrostatic equation).[2)]

Conservation Equations[3)]

A landform is the result of expression of the operation of process-response systems. A geographer investigating new aspects in the physical landscape does not always begin anew in analyzing the problem, nor does he need to amass data immediately, hoping to find clues for (stochastic) relationships or governing processes. He should know that certain principles will apply to any environmental problem of relevance to geography. Such basic principles are the conservation of energy, mass, and momentum.

The general governing equations presented below are ambitious in that they apply to a transient, three-dimensional, compressional, NEWTONian fluid. For a variety of reasons, such idealizations hardly ever will be fully used in most environmental research. For a specific problem the investigator (or instructor) need only delete terms in the equations which he deems to be negligibly small. For instance, superfluous terms result when dealing with steady flows (time derivative is set equal to zero), constant density and transport properties, one or two-dimensional flows, and others which may be judged to be insignificant based on field observations or physical intuition. Some terms may become negligible by order of magnitude estimates (for instance, creeping flows — omit inertia terms; forced flows — omit gravity forces, etc.).

A practical procedure to derive the applicable conservation equations should entail a sequence similar to the following.

1) Establishment of control volume (e.g., similar to the cube shown in Fig. 2).
2) Development of a statement which characterizes the conservation principle for the particular quantity under investigation (e.g., rate of storage within volume = net rate of input across volume boundaries + rate of production inside the volume (if applicable).
3) Determination of how the quantity is stored in the volume and how it is formulated as a time derivative.
4) Determination of whether the quantity can be produced within the volume and its rate of generation.
5) Determination of the mechanism which enable the quantity to cross the boundaries of the volume.

6) Determination of the net rate of input, using convective and diffusive transport laws.
7) Determination of the final conservation equation.

The First Law of Thermodynamics and the Total Energy Equation

The fields of fluid motion and heat flow interact because a flow of heat is superimposed on the motion. Especially relevant is the First Law of Thermodynamics: a change in total energy = heat added + work performed, or

$$dE = dh + dw. \tag{3}$$

The total energy change dE consists of changes in the internal energy U, kinetic energy K_E, and potential energy Φ. Hence,

$$dE = d(U + K_E + \Phi) = dh + dw. \tag{4}$$

If the system is abstracted into a differential "cube" ($dxdydz$) anywhere in the fluid, an open system results through which fluid flows. Then the First Law takes the form (see Notations for symbols)

$$\rho\frac{DE}{Dt} = \rho\frac{D}{Dt}(U + \tfrac{1}{2}\vec{V}\cdot\vec{V} + \Phi) = -\nabla\cdot\vec{Q} - \nabla\cdot P\vec{V} - \nabla\cdot(\vec{\tau}\cdot\vec{V}) \tag{5}$$

where $-\nabla\cdot\vec{Q}$ is the rate of heat addition by conduction, net radiative absorption, and net latent heat flux per unit volume; $\nabla\cdot P\vec{V}$ is the rate of work done by the fluid element per unit volume by pressure forces exerted on the surrounding fluid; and $\nabla\cdot(\vec{\tau}\cdot\vec{V})$ is the rate of work done per unit volume by the fluid element by virtue of viscous forces exerted on the surrounding fluid. The three terms on the right side of the equal sign represent dot products. The remainder of this section is devoted to the examination of the constituent elements of the total energy equation (5).

Conservation of Energy

Conservation of energy requires that the energy stored in the control volume $\Delta x\Delta y\Delta z$ is equal to the net input of heat across the boundaries plus the work done on the fluid in the volume plus energy produced within the volume:

$$\begin{bmatrix}\text{Rate of accumulation}\\ \text{of } U \text{ and } K_E\end{bmatrix} = \begin{bmatrix}\text{Rate of inflow of } U\\ \text{and } K_E \text{ by convection}\end{bmatrix} - \begin{bmatrix}\text{Rate of outflow of } U\\ \text{and } K_E \text{ by convection}\end{bmatrix}$$
$$+ \begin{bmatrix}\text{Net rate of heat ad-}\\ \text{dition by conduction}\end{bmatrix} + \begin{bmatrix}\text{Heat produced}\\ \text{in the volume}\end{bmatrix} - \begin{bmatrix}\text{Net rate of work done by}\\ \text{system on surroundings}\end{bmatrix} \tag{6}$$

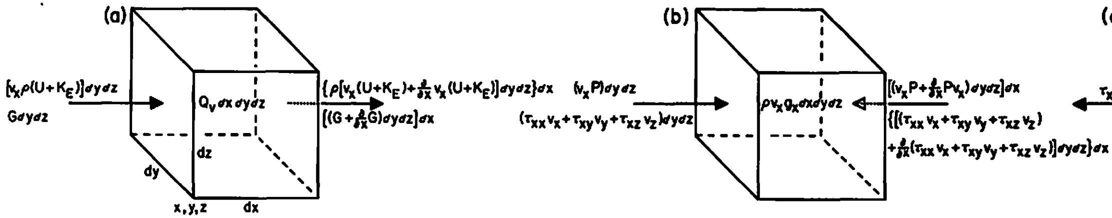
CONSERVATION OF ENERGY

ENERGY

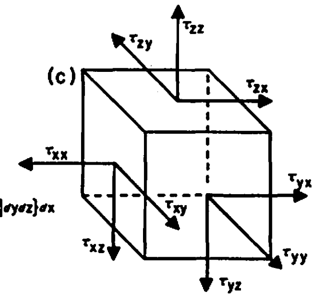
Convection (U, K_E), Conduction (G)
Volumetric Heat Source (Q_v)

RATE OF WORK

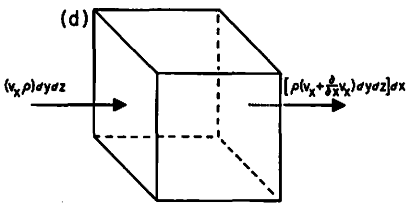
Body Force (g)
Surface Force (P, τ)



FRICTIONAL STRESSES

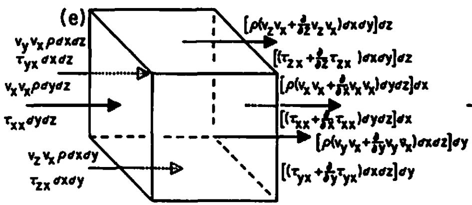


CONSERVATION OF MASS

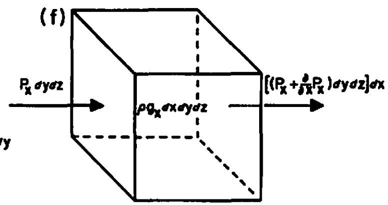


CONSERVATION OF MOMENTUM

Convection (vv)
Molecular Transfer (τ)



Fluid Pressure Force (P)
Gravitational Force (g)



This is the First Law for an open, transient system, omitting nuclear and electromagnetic energies. The potential energy Φ does not appear explicitly in (6) since it is included in the work term.

If we let our control volume approach zero for $\Delta x \Delta y \Delta z$, the rate of accumulation of internal and kinetic energy within the elemental volume is

$$dxdydz\frac{\partial}{\partial t}(\rho U + \tfrac{1}{2}\rho v^2). \tag{7}$$

The net rate of convection of internal and kinetic energy into the differential element is (Fig. 3a)

$$\begin{aligned}
&\text{x-face:} \quad && dydz\left[v_x\rho(U + \tfrac{1}{2}v^2)_x - v_x\rho(U + \tfrac{1}{2}v^2)_{x+dx}\right] + \\
&\text{y-face:} \quad && dxdz\left[v_y\rho(U + \tfrac{1}{2}v^2)_y - v_y\rho(U + \tfrac{1}{2}v^2)_{y+dy}\right] + \\
&\text{z-face:} \quad && dxdy\left[v_z\rho(U + \tfrac{1}{2}v^2)_z - v_z\rho(U + \tfrac{1}{2}v^2)_{z+dz}\right].
\end{aligned} \tag{8}$$

The net rate of heat addition by conduction G is

$$dydz(G_x - G_{x+dx}) + dxdz(G_y - G_{y+dy}) + dxdy(G_z - G_{z+dz}) \tag{9}$$

where G is given by FOURIER's law. For the x-face, the net heat inflow is $\frac{\partial}{\partial x}(k\frac{\partial T}{\partial x})dxdydz$, where k and T are the conductivity ($ML\theta^{-3}T^{-1}$, $\theta \triangleq$ time) and temperature. The sum for all faces can be written compactly as $k\nabla^2 Tdxdydz$.

The heat produced within the volume can be included as equivalent volumetric heat source terms (e.g., net radiative absorption and net liberation of latent heat),

$$Q_v dxdydz. \tag{10}$$

The rate of doing work against the three components of the volume, or body force per unit mass $\vec{g}$, is the force times the velocity,[4]

$$- \rho dxdydz(v_x g_x + v_y g_y + v_z g_z). \tag{11}$$

The minus sign results because work is done against gravity when $\underline{v}$ and $\underline{g}$ are opposed (Fig. 3b). Work can also be done against the surface forces (pressure and viscous forces). The net rate of doing work against static pressure P at the six faces of the control element is

$$dydz\left[(Pv_x)_{x+dx} - (Pv_x)_x\right] + dxdz\left[(Pv_y)_{y+dy} - (Pv_y)_y\right] + dxdy\left[(Pv_z)_{z+dz} - (Pv_z)_z\right], \tag{12}$$

Fig. 3: Derivation of the expressions for the conservation of energy, mass, and momentum for the x-components (x, y, and z components for Fig. 3c) of a fluid, differential control volume. The first and second subscript indicates the face and the direction of motion. See Notations and text for further explanations.

whereas the rate of work against viscous forces τ is (Fig. 3b, c)

$$dydz[(\tau_{xx}v_x + \tau_{xy}v_y + \tau_{xz}v_z)_{x+dx} - (\tau_{xx}v_x + \tau_{xy}v_y + \tau_{xz}v_z)_x] +$$
$$dxdz[(\tau_{yx}v_x + \tau_{yy}v_y + \tau_{yz}v_z)_{y+dy} - (\tau_{yx}v_x + \tau_{yy}v_y + \tau_{yz}v_z)_y] +$$
$$dxdy[(\tau_{zx}v_x + \tau_{zy}v_y + \tau_{zz}v_z)_{z+dz} - (\tau_{zx}v_x + \tau_{zy}v_y + \tau_{zz}v_z)_z]. \quad (13)$$

Substituting equations (7) to (13) into equation (6) and dividing by dxdydz, results in

$$\frac{\partial}{\partial t}(\rho U + \tfrac{1}{2}\rho v^2) = - [\frac{\partial}{\partial x}v_x\rho(U + \tfrac{1}{2}v^2) + \frac{\partial}{\partial y}v_y\rho(U + \tfrac{1}{2}v^2) + \frac{\partial}{\partial z}v_z\rho(U + \tfrac{1}{2}v^2)]$$
$$- (\frac{\partial G_x}{\partial x} + \frac{\partial G_y}{\partial y} + \frac{\partial G_z}{\partial z}) + Q_v + \rho(v_x g_x + v_y g_y + v_z g_z) - (\frac{\partial}{\partial x}Pv_x + \frac{\partial}{\partial y}Pv_y + \frac{\partial}{\partial z}Pv_z)$$
$$- [\frac{\partial}{\partial x}(\tau_{xx}v_x + \tau_{xy}v_y + \tau_{xz}v_z) + \frac{\partial}{\partial y}(\tau_{yx}v_x + \tau_{yy}v_y + \tau_{yz}v_z)$$
$$+ \frac{\partial}{\partial z}(\tau_{zx}v_x + \tau_{zy}v_y + \tau_{zz}v_z)]. \quad (14)$$

In vector notation, for notational convenience, and as seen by a stationary observer (EULERian frame — only the fluid field changes, not the element), (14) becomes:

$$\frac{\partial}{\partial t}\rho(U + \tfrac{1}{2}v^2) = - [\nabla\cdot\rho\vec{V}(U + \tfrac{1}{2}v^2)] - \nabla\cdot\vec{G} + Q_v + \rho(\vec{V}\cdot\vec{g}) - \nabla\cdot P\vec{V} - \nabla\cdot(\vec{\tau}\cdot\vec{V}). \quad (15)$$

Thus, the rate of gain of energy (per unit volume) = - rate of energy input by convection - conduction + volumetric heat source + rate of work done on the element by gravitational forces - rate of work done on the element by pressure forces - rate of work done on the element by viscous forces.

Moving the convection term to the left and carrying out the differentiation on the left, results in

$$\rho[\frac{\partial}{\partial t}(U + \tfrac{1}{2}v^2) + \vec{V}\cdot\nabla(U + \tfrac{1}{2}v^2)] + (U + \tfrac{1}{2}v^2)[\frac{\partial\rho}{\partial t} + (\nabla\cdot\rho\vec{V})] =$$
$$- \nabla\cdot\vec{G} + Q_v + \rho(\vec{V}\cdot\vec{g}) - \nabla\cdot P\vec{V} - \nabla\cdot(\vec{\tau}\cdot\vec{V}). \quad (16)$$

Since the first term on the left is density times the substantial derivative of $(U + \tfrac{1}{2}v^2)$ and the second term on the left is equal to zero because of the equation of continuity [equation (21) below], the fluid element is now in a LAGRANGian frame (the flow field and the element change with time), as if seen by an observer moving with the fluid. Hence,

$$\rho\frac{D}{Dt}(U + \tfrac{1}{2}v^2) = - \nabla\cdot\vec{G} + Q_v + \rho(\vec{V}\cdot\vec{g}) - \nabla\cdot P\vec{V} - \nabla\cdot(\vec{\tau}\cdot\vec{V}). \quad (17)$$

Conservation of Mass

Mass can be stored within a control volume by a change in density, whereas the boundaries can be crossed by convection at the mass average velocity. The mass balance over a stationary elemental cube is (Fig. 3d):

$$\begin{bmatrix}\text{Rate of mass}\\ \text{accumulation}\end{bmatrix} = \begin{bmatrix}\text{Rate of mass}\\ \text{in}\end{bmatrix} - \begin{bmatrix}\text{Rate of mass}\\ \text{out}\end{bmatrix} \text{, or} \tag{18}$$

$$dxdydz\frac{\partial\rho}{\partial t} = dydz\left[(\rho v_x)_x - (\rho v_x)_{x+dx}\right] + dxdz\left[(\rho v_y)_y - (\rho v_y)_{y+dy}\right] + dxdy\left[(\rho v_z)_z - (\rho v_z)_{z+dz}\right]. \tag{19}$$

Dividing by $dxdydz$ and subtracting the outflow from the inflow, expanding a quantity evaluated at $x+dx$, $y+dy$, and $z+dz$ in a TAYLOR series, and cancelling terms which subtract out, results in the equation of continuity in the EULERian frame:

$$\frac{\partial\rho}{\partial t} = -\left(\frac{\partial}{\partial x}\rho v_x + \frac{\partial}{\partial y}\rho v_y + \frac{\partial}{\partial z}\rho v_z\right), \text{ or} \tag{20}$$

$$\frac{\partial\rho}{\partial t} + \nabla\cdot\rho\vec{V} = \vec{0}. \tag{21}$$

This describes the rate of change of density ρ resulting from changes in the mass velocity vector $\rho\vec{V}$ and its divergence. Performing the differentiation of (20) and collecting all derivatives of ρ on the left side, results in the LAGRANGian version of the continuity equation:

$$\frac{\partial\rho}{\partial t} + v_x\frac{\partial\rho}{\partial x} + v_y\frac{\partial\rho}{\partial y} + v_z\frac{\partial\rho}{\partial z} = -\rho\left(\frac{\partial v_x}{\partial x} + \frac{\partial v_y}{\partial y} + \frac{\partial v_z}{\partial z}\right), \text{ or} \tag{22}$$

$$\frac{D\rho}{Dt} + \rho(\nabla\cdot\vec{V}) = \vec{0}. \tag{23}$$

A special form of (23), often used in the environmental sciences, is for an incompressible fluid (constant density, $D\rho/Dt = 0$),

$$\nabla\cdot\vec{V} = \vec{0}. \tag{24}$$

No fluid is truly incompressible, but often only a small error is introduced by making that assumption.

In order to separate the internal energy $\rho\underline{U}$ from the kinetic energy $\frac{1}{2}\rho v^2$ in equation (17), the equation of motion has to be developed first (see below).

Conservation of Chemical Species

Since this is very similar to the mass treatment, only an abbreviated version will be given. The species balance in the control volume is: (25)

$$\begin{bmatrix}\text{Rate of species } i\\ \text{accumulation}\end{bmatrix} = \begin{bmatrix}\text{Net rate of inflow of}\\ \text{species by convection}\\ \text{and diffusion}\end{bmatrix} + \begin{bmatrix}\text{Production rate of}\\ \text{species } i \text{ in volume due}\\ \text{to chemical reaction}\end{bmatrix}$$

or

$$\frac{\partial \rho_i}{\partial t} dxdydz = - \nabla\cdot(\rho_i \cdot \vec{V})dxdydz - \nabla\cdot\vec{j}_i dxdydz + p_i dxdydz. \tag{26}$$

In the LAGRANGian framework this becomes

$$\frac{D\rho_i}{Dt} + \rho_i(\nabla\cdot\vec{V}) + \nabla\cdot\vec{j}_i - p_i = \vec{0}. \tag{27}$$

Conservation of Momentum

The fundamental principle of motion is NEWTON's Second Law. For an elemental volume, momentum (mass x velocity) is conserved as follows:

$$\begin{bmatrix}\text{Rate of momentum}\\ \text{accumulation}\end{bmatrix} = \begin{bmatrix}\text{Rate of momentum}\\ \text{in}\end{bmatrix} - \begin{bmatrix}\text{Rate of momentum}\\ \text{out}\end{bmatrix} + \begin{bmatrix}\text{Sum of forces acting}\\ \text{on the system}\end{bmatrix} \tag{28}$$

Momentum exchanges occur by convection (bulk fluid flow) and by molecular transfer (via virtue of velocity gradients only). Keeping in mind that mass transfer equals $\rho\underline{v}$ and $(\rho\underline{v})\underline{v}$ is momentum, the net convective x-momentum flowing into the control element is (Fig. 3e)

$$dydz\left[(\rho v_x v_x)_x - (\rho v_x v_x)_{x+dx}\right] + dxdz\left[(\rho v_y v_x)_y - (\rho v_y v_x)_{y+dy}\right] + dxdy\left[(\rho v_z v_x)_z - (\rho v_z v_x)_{z+dz}\right], \tag{29}$$

whereas the net molecular transport of x-momentum is

$$dydz\left[(\tau_{xx})_x - (\tau_{xx})_{x+dx}\right] + dxdz\left[(\tau_{yx})_y - (\tau_{yx})_{y+dy}\right] + dxdy\left[(\tau_{zx})_z - (\tau_{zx})_{z+dz}\right] \tag{30}$$

where the first and second subscript indicates the face and the direction of the motion, respectively (e.g., τ_{xx} is the normal stress on the x-face, whereas τ_{yx} is the x-directed tangential shearing stress on the y-face resulting from viscous forces — see Fig. 3c).

The forces acting on the system arise from fluid pressure P and gravitational force per unit mass $\vec{g}$. The resultant of these forces in the x-direction is (Fig. 3f):

$$dydz\left[(P)_x - (P)_{x+dx}\right] + \rho g_x dxdydz \tag{31}$$

where pressure in a moving fluid is defined by the equation of state

$$P = \rho RT \tag{32}$$

where T is the absolute temperature.

The rate of accumulation of x-momentum within the element is

$$dxdydz\left(\frac{\partial \rho v_x}{\partial t}\right) \tag{33}$$

Dividing both sides of the above equations by $dxdydz$ and substituting them into equation (28), gives the equation of motion for the x-component in the EULERian frame:

$$\frac{\partial}{\partial t}\rho v_x = -\left(\frac{\partial}{\partial x}\rho v_x v_x + \frac{\partial}{\partial y}\rho v_y v_x + \frac{\partial}{\partial z}\rho v_z v_x\right) - \left(\frac{\partial}{\partial x}\tau_{xx} + \frac{\partial}{\partial y}\tau_{yx} + \frac{\partial}{\partial z}\tau_{zx}\right) - \frac{\partial P}{\partial x} + \rho g_x \tag{34}$$

which reads: accumulation of momentum = - net convective momentum - net molecular momentum - net pressure forces + gravitational forces. The y and z-components are similar to (34). Consequently, for all three components, v_x, v_y, v_z make up the mass velocity vector $\rho\vec{v}$; g_x, g_y, g_z make up the gravitational acceleration $\vec{g}$; $\partial P/\partial x$, $\partial P/\partial y$, $\partial P/\partial z$ make up the vector ∇P ("gradient of P"), $\rho v_x v_x$, $\rho v_x v_y$, $\rho v_x v_z$, $\rho v_y v_z$, $\rho v_y v_y$, $\rho v_y v_z$, $\rho v_z v_x$, $\rho v_z v_y$, $\rho v_z v_z$ make up the convective momentum flux $\rho\vec{v}\vec{v}$ (which is a dyadic product of $\rho\vec{v}$ and $\vec{v}$), and τ_{xx}, τ_{xy}, τ_{xz}, τ_{yx}, τ_{yy}, τ_{yz}, τ_{zx}, τ_{zy}, τ_{zz} are the elements of the stress tensor $\vec{\tau}$. Then the equation of motion (EULERian) in vector form is

$$\frac{\partial}{\partial t}\rho\vec{V} = -\nabla\cdot\rho\vec{V}\vec{V} - \nabla P - \nabla\cdot\vec{\tau} + \rho\vec{g} \tag{35}$$

which can be read like (34).

Using equation (34), differentiating and rearranging, with the aid of the equation of continuity (23), results in the LAGRANGian version of the equation of motion for the x-component:

$$\rho\frac{Dv_x}{Dt} = -\frac{\partial P}{\partial x} - \left(\frac{\partial}{\partial x}\tau_{xx} + \frac{\partial}{\partial y}\tau_{yx} + \frac{\partial}{\partial z}\tau_{zx}\right) + \rho g_x. \tag{36}$$

When all three components(x, y, z)are added vectorially and the often omitted CORIOLIS acceleration $2\vec{\Omega}\times\vec{V}$ (a cross product) is included, the final LAGRANGian equation of motion results.[5)]

$$\rho\frac{D\vec{V}}{Dt} = -\nabla P - \nabla\cdot\vec{\tau} + \rho\vec{g} - 2\vec{\Omega}\times\vec{V} \tag{37}$$

where $D\vec{V}/Dt$ is the substantial derivative for a vector field, $D\vec{V}/Dt = \partial\vec{V}/\partial t + (\vec{V}\cdot\nabla)\vec{V}$ for rectangular coordinates, and $\vec{\Omega}$ is the angular velocity vector. In this form, the equation of motion (37) states that a volume element moving with the fluid is accelerated because of forces acting on it. This is an expression of NEWTON's Secound Law: mass (per unit volume) times acceleration = sum of forces, Ma = F (i.e., - net pressure force on the element - net molecular momentum of the viscous forces on the element + gravitational forces on the element - CORIOLIS force).

The body forces are to be regarded as given external forces, but the surface forces depend on the rate at which the fluid is strained by the velocity field present in it. The system of forces determines a state of stress and in order to use these equations, we need to insert expressions for the various stresses in terms of velocity gradients and fluid properties. We are confining ourselves to isotropic NEWTONian fluids.[6]
It can be shown that the following relations hold:[7]

$$\begin{aligned} \tau_{xx} &= -2\mu\frac{\partial v_x}{\partial x} + \frac{2}{3}\mu(\nabla\cdot\vec{V}) \\ \tau_{yy} &= -2\mu\frac{\partial v_y}{\partial y} + \frac{2}{3}\mu(\nabla\cdot\vec{V}) \\ \tau_{zz} &= -2\mu\frac{\partial v_z}{\partial z} + \frac{2}{3}\mu(\nabla\cdot\vec{V}) \end{aligned} \tag{38}$$

and the angular rate of change is given by

$$\begin{aligned} \tau_{xy} = \tau_{yx} &= -\mu\left(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x}\right) \\ \tau_{yz} = \tau_{zy} &= -\mu\left(\frac{\partial v_y}{\partial z} + \frac{\partial v_z}{\partial y}\right) \\ \tau_{zx} = \tau_{xz} &= -\mu\left(\frac{\partial v_z}{\partial x} + \frac{\partial v_x}{\partial z}\right) \end{aligned} \tag{39}$$

The above expressions are generalizations of NEWTON's law of viscosity

$$\tau = -\mu\frac{\partial v}{\partial y} \tag{40}$$

applied to complex flows with a fluid flowing in all directions, where μ is the dynamic viscosity of the fluid $(ML^{-1}\theta^{-1})$.

Substituting the above τ's into the equation of motion (36), including all $\underline{x}$, $\underline{y}$, and $\underline{z}$ components, results in

$$\rho\frac{Dv_x}{Dt} = -\frac{\partial P}{\partial x} + \frac{\partial}{\partial x}\{2\mu\frac{\partial v_x}{\partial x} - \frac{2}{3}\mu(\nabla\cdot\vec{V})\} + \frac{\partial}{\partial y}\{\mu(\frac{\partial v_x}{\partial y} + \frac{\partial v_y}{\partial x})\} + \frac{\partial}{\partial z}\{\mu(\frac{\partial v_z}{\partial x} + \frac{\partial v_x}{\partial z})\}$$
$$+ \rho g_x + C_x$$
$$\rho\frac{Dv_y}{Dt} = -\frac{\partial P}{\partial y} + \frac{\partial}{\partial x}\{\mu(\frac{\partial v_y}{\partial x} + \frac{\partial v_x}{\partial y})\} + \frac{\partial}{\partial y}\{2\mu\frac{\partial v_y}{\partial y} - \frac{2}{3}\mu(\nabla\cdot\vec{V})\} + \frac{\partial}{\partial z}\{\mu(\frac{\partial v_z}{\partial y} + \frac{\partial v_y}{\partial z})\}$$
$$+ \rho g_y + C_y$$
$$\rho\frac{Dv_z}{Dt} = -\frac{\partial P}{\partial z} + \frac{\partial}{\partial x}\{\mu(\frac{\partial v_z}{\partial x} + \frac{\partial v_x}{\partial z})\} + \frac{\partial}{\partial y}\{\mu(\frac{\partial v_z}{\partial y} + \frac{\partial v_y}{\partial z})\} + \frac{\partial}{\partial z}\{2\mu\frac{\partial v_z}{\partial z} - \frac{2}{3}\mu(\nabla\cdot\vec{V})\}$$
$$+ \rho g_z + C_z \tag{41}$$

where the $\underline{C}$'s are the components of the CORIOLIS force [$C_x = 2\Omega(v_y\sin\phi - v_z\cos\phi)$; $C_y = -2\Omega v_x\sin\phi$; $C_z = 2\Omega v_x\cos\phi$; $\vec{C} = -2\vec{\Omega}\times\vec{V}$; $\phi=$ latitude]. Forming the basis of the sciene of fluid mechanics, these equations [three components of (41)], the equation of state (32), the density dependence of viscosity [$\mu = 1/3(\rho v \ell) = f(T)$], the equation of continuity (23), and the equation of internal energy [equation (49) or (50) below] constitute seven equations for the seven unknowns $\underline{v}_x$, $\underline{v}_y$, $\underline{v}_z$, $\underline{P}$, ρ, $\underline{T}$, μ. Given the initial conditions and the boundary conditions, this closed set of equations completely determines the motion of a compressible fluid. For an isothermal fluid, the set reduces to five equations [the three equations of (41), (23), and (32)] and the five variables $\underline{v}_x$, $\underline{v}_y$, $\underline{v}_z$, $\underline{P}$, ρ.

The equations of motion are often used in some restricted form. For constant density, i.e., $\nabla\cdot\vec{V} = \vec{0}$, via the continuity equation (24) and omitting CORIOLIS force, this results in the NAVIER-STOKES equation (1822):

$$\rho\frac{D\vec{V}}{Dt} = -\nabla P + \mu\nabla^2\vec{V} + \rho\vec{g}. \tag{42}$$

For a constant-density, frictionless fluid (u = 0), the EULER equation (1755) is obtained:

$$\rho\frac{D\vec{V}}{Dt} = -\nabla P + \rho\vec{g}. \tag{43}$$

Mechanical (Kinetic)Energy

We now use the equation of motion (37), forming a scalar product by dotting both sides of the equation with $\vec{v}$, to obtain the kinetic energy equation

$$\rho\frac{D}{Dt}(\tfrac{1}{2}\vec{V}\cdot\vec{V}) = -(\vec{V}\cdot\nabla P) - \{\vec{V}\cdot(\nabla\cdot\vec{\tau})\} + \rho(\vec{V}\cdot\vec{g}). \tag{44}$$

In words: change of kinetic energy = - work done on the element by pressure forces - work done on the element by force of friction + rate of work done by gravity on the element as a result of vertical displacement. The CORIOLIS force does no work $[(-2\vec{\Omega}\times\vec{V})\cdot\vec{V} = \vec{0}]$ and only affects the direction of the velocity vector. Equation (44) then describes the rate of change of kinetic energy per unit mass for an element of fluid moving downstream (LAGRANGian). To obtain the EULERian version of this equation, we rewrite in terms of $\partial/\partial t$ and split up the pressure and viscous contributions into two terms. This results in a stationary cube through which fluid flows:

$$\frac{\partial}{\partial t}(\tfrac{1}{2}\rho v^2) = -(\nabla\cdot\tfrac{1}{2}\rho v^2\vec{V}) - \nabla\cdot P\vec{V} - P(-\nabla\cdot\vec{V}) - \{\nabla\cdot(\vec{\tau}\cdot\vec{V})\}$$
$$-(-\vec{\tau}:\nabla\vec{V}) + \rho(\vec{V}\cdot\vec{g}). \tag{45}$$

Or, a rate increase in kinetic energy per unit volume = - net input of kinetic energy by advection (convection) - rate of work done by pressure forces on the element through displacement at the boundary (internal work) - rate of reversible conversion to internal energy by compression or expansion (external work — adiabatic changes) - rate of work done by viscous forces on the element - rate of irreversible conversion to internal energy (frictional heating, a double dot product) + rate of work done by gravity on the element as a result of vertical displacement, i.e., conversion of geopotential energy into kinetic energy.

Moving the first term on the right (advection) of equation (45) to the left side, results in the LAGRANGian version of (45):

$$\rho\frac{D}{Dt}(\tfrac{1}{2}v^2) = P(\nabla\cdot\vec{V}) - (\nabla\cdot P\vec{V}) + \rho(\vec{V}\cdot\vec{g}) - \{\nabla\cdot(\vec{\tau}\cdot\vec{V})\} + \vec{\tau}:\nabla\vec{V} \tag{46}$$

Later we will use the terms $P(\nabla\cdot\vec{V})$ and $(\vec{\tau}:\nabla\vec{V})$ in the equation of internal energy. Using equations (38) and (39), the viscous dissipation function is

$$\Phi_v = 2\{(\frac{\partial v_x}{\partial x})^2 + (\frac{\partial v_y}{\partial y})^2 + (\frac{\partial v_z}{\partial z})^2\} + (\frac{\partial v_y}{\partial x} + \frac{\partial v_x}{\partial y})^2 + (\frac{\partial v_z}{\partial y} + \frac{\partial v_y}{\partial z})^2$$
$$+ (\frac{\partial v_x}{\partial z} + \frac{\partial v_z}{\partial x})^2 - \frac{2}{3}(\nabla\cdot\vec{V})^2 \tag{47}$$

or

$$(-\vec{\tau}:\nabla\vec{V}) = \mu\Phi_v = \tfrac{1}{2}\mu\sum_{i}^{3}\sum_{j}^{3}\{(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i}) - \frac{2}{3}(\nabla\cdot\vec{V})\delta_{ij}\}^2 \tag{48}$$

where $\delta_{i,j}$ is the KRONECKER Delta ($\delta_{i,j} = 1$ for $i = j$; $\delta_{i,j} = 0$ for $i \neq j$). The viscous dissipation function represents the degradation of mechanical (kinetic) energy to thermal heat (actually a "volumetric heat source"). In most cases, except for high-speed flows, this is a negligible term.

Internal (Thermal) Energy

By subtraction of the kinetic energy equation (46) from the equation of energy (17) we obtain the internal energy equation:

$$\rho\frac{DU}{Dt} = - \nabla\cdot\vec{G} + Q_v - P(\nabla\cdot\vec{V}) - \vec{\tau}:\nabla\vec{V} \tag{49}$$

or, the rate of gain of internal energy per unit volume = - rate of input of energy by conduction + heat produced within the element (e.g., net radiative absorption, net latent heat absorption) - adiabatic rate of internal energy increase - viscous dissipation of mechanical to thermal energy. The last two terms on the right side of the equal sign are common to both the kinetic energy equation (46) and the internal energy equation (49), appearing with opposite signs. The adiabatic term is positive when the fluid is expanding and negative for contraction.

It is more common to have the thermal energy equation in terms of a fluid temperature and heat capacity rather than internal energy. For a compressible fluid with constant thermal conductivity $\underline{k}$, the equation of change of temperature is

$$\rho c_v\frac{DT}{Dt} = k\nabla^2 T + Q_v - P(\nabla\cdot\vec{V}) - (\vec{\tau}:\nabla\vec{V}). \tag{50}$$

Summary

We are now in a position to reconstruct the original total energy equation (5). The potential energy is

$$\rho\frac{D\Phi}{Dt} = - \rho(\vec{V}\cdot\vec{g}). \tag{51}$$

Combining conduction and the volumetric heat source, $-\nabla\cdot\vec{Q} = -\nabla\cdot\vec{G} + Q_v$, and adding (51) to (49), results in the thermal and potential energy

$$\rho\frac{D}{Dt}(U + \Phi) = - (\nabla\cdot\vec{Q}) - P(\nabla\cdot\vec{V}) - (\vec{\tau}:\nabla\vec{V}) - \rho(\vec{V}\cdot\vec{g}), \tag{52}$$

and by adding the kinetic energy equation (46), we arrive at our previous point of departure, the total energy equation:

$$\rho\frac{DE}{Dt} = \rho\frac{D}{Dt}(U + \tfrac{1}{2}\vec{V}\cdot\vec{V} + \Phi) = - \nabla\cdot\vec{Q} - \nabla\cdot P\vec{V} - \nabla\cdot(\vec{\tau}\cdot\vec{V}) \tag{5}$$

The expressions of the basic principles of the conservation of energy, mass, and momentum, discussed above, comprise an impressive set of simultaneous partial differential equations with the four independent variables of $\underline{x}$, $\underline{y}$, $\underline{z}$, and $\underline{t}$. Ideally, these equations (with the proper initial and boundary conditions) should determine the state of many morphological components of the physical landscape. Unfortunately, general solutions, even by numerical methods, of the complete set of equations is beyond current capabilities, but many problems of interest to the physical geographer can be described adequately by simplified forms and parameterizations of the ideal conservation equations. Thus, this presents a major challenge to the geographer interested in applying the concept of process-response systems to the physical environment of man.

II. APPLICATIONS

There are two energy sources of importance in the creation of physical landscapes: The solar energy cascade (external) and the tectonic energy cascade (internal). Both cascades, though operating on vastly different time scales of oscillation, are "forcing" the responses of the subsystems of the earth-atmosphere system, i.e., atmosphere and planetary boundary layer PBL, lithosphere, oceans, cryosphere (ice), animal systems, vegetation, soils, groundwater systems, and the man systems (Fig. 4). Because man increasingly is interfering with the exchanges

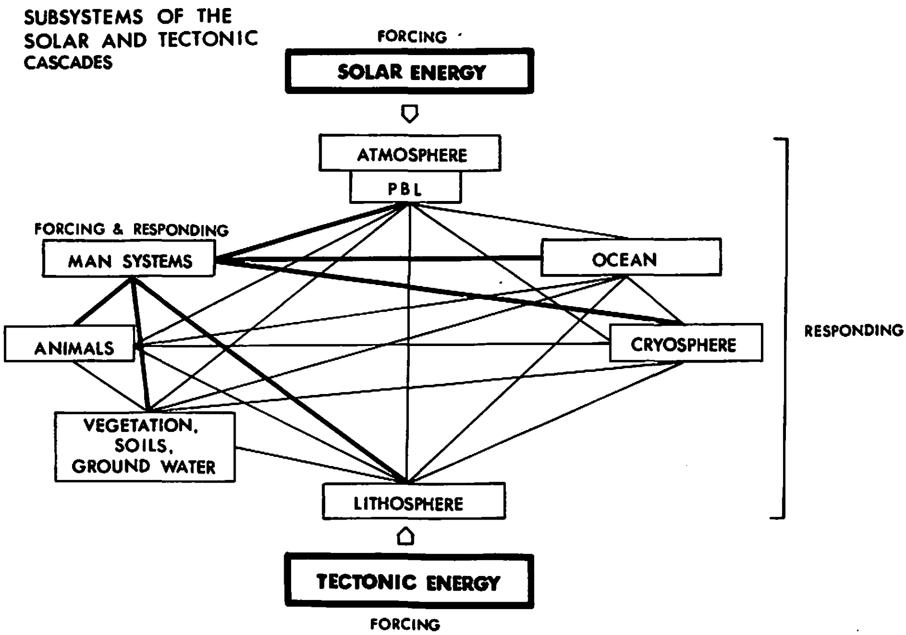


Fig. 4: Subsystems of the solar and tectonic cascades. PBL = planetary boundary layer.

of energy, mass, and momentum (via the flow of "information" and subsequent actions, through decision-making systems), one can assume that man systems are both forcing and responding. The tectonic cascade influences the lithosphere especially by tectonic plate movements and associated mountain-building. The PBL can also be influenced by the volcanic emission of CO_2. The other linkages between the atmosphere-PBL system and the man system are obvious (e. g., creation of urban climates, air pollution, effects on physiology, etc.), as are connections between the various subsystems. This figure could be considered to represent physical geography as the application of physics and socioeconomic processes to the environment.[8] In that vein, physical geography investigates the varying responses to different inputs, throughputs, and outputs of energy, mass, momentum, and information to portions of the landscape envelope of interest to mankind.

Since the 1960's, and with acceleration in the last five years, a philosophical and associated methodogical revolution has been in progress with respect to the analysis of the physical landscape envelope or soil-plant-atmosphere continuum. The more non-atmospherically oriented aspects of this movement often appear under labels of hydrogeomorphology, hydrology, watershed modeling, groundwater flow, civil engineering, etc.[9] Temporarily omitting the PBL, this new movement is an attempt to develop a greater understanding of the cause and effect mechanisms operating in the landscape, through deterministic or parametric modeling. More specifically, the purpose of hydrological process-response models is to synthesize past events, predict future events, evaluate the impact of man on the landscape, and to improve the understanding of geomorphic processes.[10] Deterministic models, making use of established laws of thermo- and hydrodynamics (conservation of energy, mass, and momentum — see I. Basic Theory), are expressed in closed sets of partial differential equations. Such equations, when initial and boundary conditions are prescribed, potentially provide a temporal and spatial output which is known with certainty.[11] The operation of such ideal, transient, three-dimensional models, to be solved by numerical methods, would require the model definition input (e. g., the size of the nodal grid system or finite element structure, the duration of discrete time steps, the landscape dimensions), the climatic input (preferably a numerical model of the PBL), the flow parameter input (e. g., slope, roughness, hydraulic radii of streams, permeabilities, etc.), and the partial differential equations applicable to the fluid mechanics of hydrological processes.[12]

At the other end of a continuum of certainty of cause and effect is stochasticism, where nature is viewed as chaotic and all events are seen as chance or random results — the researcher has no information as to cause and effect.[13] An intermediate position is occupied by parametric models where some notions as to cause and effect exists, but often the required information for the rigorous mathematics of determinism does not yet exist.[14] The black boxes of parametric models are often considered as stepping stones to higher levels of understanding. Parametric models make use of historical and known physical characteristics of, for instance, a drainage area and attempt to make use of empirical realtionships between elements of such data if deductive links are not well known or are too complex to apply. Thus, many parametric modelers consider themselves to be advancing toward determinism.

Among the advantages of a deductive stance is the possibility of the translation of the results of one discipline into the language of another field. With some insight into analogue quantities and scale factors (laws of similitude), problems solved in one discipline may be transferred to another. An example would be the LaPLACE equation (steady state heat conduction — related to equation (9), I. Basic Theory) which appears in hydrodynamics, thermodynamics, electrodynamics, electrostatics. [15]

Currently, probabilistically-based models produce better predictions than deterministic or parametric models, but these predictions are specific to area, time, or other local circumstance and, thus, cannot be safely applied beyond the rather narrow data base from which the original model was developed. Consequently, stochastic models lack the promise of generality with the revelation of causal relations, which is one of the main potential attractions of deductive models.

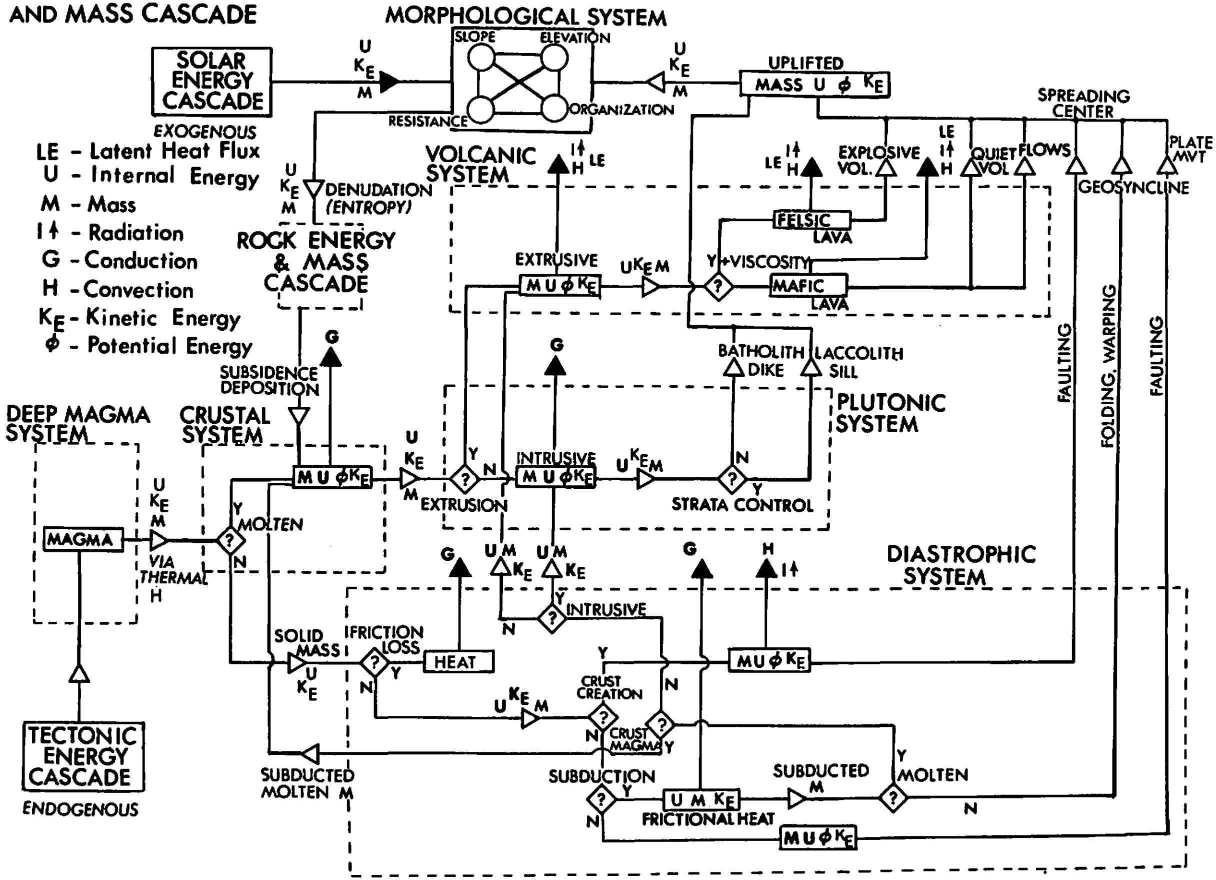
The concept of determinism in modeling has drawn criticism. For instance, YEVJEVICH argues that it is very difficult to find a pure deterministic hydrological process in nature. [16] He contends that the controversy between determinism and stochasticism has a long history and that a combined approach would be more rewarding. Probably few will argue for a possible case of complete determinism (white box) and it appears, depending on one's viewpoint, that it is a matter of how much "residual noise" (uncertainty) one is willing to accept as inevitable. The researcher leading toward deduction believes that this remnant, unexplained noise can be further reduced, than a scholar working inductively would admit. Some of the contraversy appears to be a war of words and to be irrelevant because scholars seem to differ in their definitions as to what constitutes a deterministic or stochastic model. Clarke offers four basic model possibilities:
stochastic-conceptual, stochastic-empirical, deterministic-conceptual, and deterministic-empirical. [17]

The literature on deterministic and parametric modeling is already extensive, but little recognition has been given to this important development by geographers. For instance, the leading texts, commonly addressing themselves to geographers, tend to slight research of workers in other fields using such approaches to the understanding of landscape features. [18] Again, I am not implying that I advocate an overthrow of current effective methods in physical geography, but I am suggesting that the research and teaching focus could be broadened. In fact, for instance, field work in geomorphology is badly needed for model validation or generation. I ask only that data collection should not be considered an end in itself and should be physically significant. The answers to geographical problems are not necessarily always apparent in the field. Observations may often only be explainable by resort to theory. The more obvious and more easily measured morphological features of the landscape are created by the largely hidden processes of the exchanges of energy, mass, and momentum.

Geodynamic Systems

Parts of this paper are divided into geodynamic systems (endogenetic) and

TECTONIC ENERGY AND MASS CASCADE



geomorphological systems (exogenetic). The assumption is made, based on a cursory literature search, that geodynamic systems, operating generally on a different time scale compared to geomorphic systems, do not typically belong to the domain of active research by geographers. Such systems could be conceived to be an introduction or stage-setting to, or partial cause of, the present landscape. Thus, no attempt has been made to comment on the literature of geodynamics except for its pedagogical aspects.

One of the clearest ways of demonstrating the above concepts is by the use of canonical structures which aid in the simplification and generalization of complex structures or systems.[19] For instructional purposes this is also a logical starting point and one of the simplest ways of introducing and applying process-response systems.

The tectonic and solar cascade are the two poles of energy potential between the diastrophic, plutonic, and volcanic systems (Fig. 5). This extremely simplified system is probably more of pedagogical concern in teaching general physical

Fig. 5: Tectonic process-response system.
Rectangle = storage; diamond shape = flow regulator; arrow = input or output; Y = yes; N = no. See Notations for other symbols. The morphological system (top of graph) is the major site where the uplifted mass (as a result of the exchanges of energy, mass, and momentum in the various subsystems) is subjected to the downwearing energies of the solar cascade. The tectonic energy cascade (bottom) influences by its internal and kinetic energy (via convection currents) the state of the deep magma (located in storage box). This state is represented by its internal energy $\underline{U}$, potential energy Φ, kinetic energy $\underline{K}_E$, and mass $\underline{M}$. The deep magma (output of $\underline{U}$, $\underline{K}_E$, and $\underline{M}$), in turn, influences the same components located near the planet's surface, abstracted as crustal system. This latter storage contains not only molten materials directly from the earth's interior, but also molten material or "igneous mush" resulting from the subduction of tectonic plates. Mass can issue from the crustal system either in a molten state (to be allocated to plutonic system) or in a solid state, entering the diastrophic system. Assuming the former, a second regulator makes choices between extrusive and intrusive storage. This latter storage can be shunted between flows resulting in the morphological features of batholiths, dikes, etc., and flows creating laccoliths and sills because of strata control. Both groups of internal structures can, in time, become uncovered by erosion, joining the uplifted mass (dendritic drainage). In the volcanic subsystem allocations of energy, mass, and momentum are made between highly viscous felsic lavas, resulting in explosive volvanoes and fissure flows. The energy output of lava occurs also by reradiation $\underline{I}\uparrow$, sensible heat $\underline{H}$ and latent $\underline{LE}$ heat fluxes. The lava flows become part of the uplifted mass storage having its characteristic components of $\underline{U}$, $\underline{K}_E$, and Φ. When tracing the path of energy and mass in the diastrophic system, frictional heating [equation (48) I. Basic Theory] might be a byproduct (output by conduction $\underline{G}$) of this movement of solid or plastic masses. Other regulators decide between creation of crust — leading to spreading centers (mid-ocean ridge, rift, graben), and the subduction or destruction of crust. This subduction can result in molten mass (to be redirected either to the plutonic system by intrusion, or to the deeper crustal system) or mass can be transported by lithospheric plate movement, accompanied by faulting (rectangular drainage), folding (trellis drainage), and warping (geosyncline, island arc, sea trench). The downwearing energies of the solar cascade will impinge upon the uplifted mass created by the tectonic cascade. The result of this confrontation is generalized in the morphological system which abstracts topography simply into aspects of slope, elevation, resistance, and general organization of topographic features. By a rock energy and mass cascade, mass could enter again (depending on the dynamic relations between Φ, entropy, and denudation) the crustal system, completing the cycle.

geography, since few geographers are actively engaged in research in such aspects of geophysics. On the other hand, interest in the effects of the solar cascade on the landscape has been a long-standing tradition among geographers.

Geomorphological Systems

For purposes of demonstration, only a few selections are made from among the many possible subsystems influenced by the solar cascade (Fig. 6). In this scheme, energy, mass, and momentum are seen as cascading from the earth-atmopshere process-response system to the ice, land, and ocean interfaces. For instance, the land surface is visualized to be undergoing weathering, resulting in characteristic soil, slope, and vegetation conditions. The mass output from these systems is transported to stream channel and beach systems, with the ocean as the ultimate terminal for debris (though having feedback for evaporation to the PBL). It is not to be construed that the oceans are the final sink for all debris in the DAVISian static sense — tectonic uplifts can turn a sink into a source.

Whereas man appears to have little influence on the rather ponderous workings of the tectonic cascade, operating on the time scale of centuries, his presence can be felt in the subsystems dominated by the solar cascade. At this time scale and level, systems become physical-human process-response systems where physical processes are linked to socioeconomic decision-making systems. Key components are often controlled by intelligence (usually via the more sensitive regulator and storage variables), resulting in the throughput of energy, mass, momentum, and information. In such systems, the basic question often to be answered is: How can we intervene in a planned and predictable manner, beneficial to man and without inadvertent or unforeseen secondary effects? Man's perception of nature, a possible continuum from mastery over nature, integration with nature, to his subordination to nature, becomes of utmost importance. Here is a locus where physical and human geographers need to join in research relevant to society and other academic disciplines.

The drainage basin process-response system is abstracted into only eight subsystems: weathering, debris, soil-groundwater stream channel, wave, ocean, atmosphere, and decision-making (Fig. 7). The area labeled "boundary layer", though having physical meaning, has mainly been created here to facilitate the drawing of the graph. In addition to its existence as an imaginary sheath of air surrounding all interfaces, it also serves symbolically as a reminder that all subsystems are interrelated and are simultaneously and synergistically affecting each other.

In the weathering system, water, biochemicals, clastic debris, and energy (mainly in the form of heat) are cascaded through the various subsystems of soil and rock layers, altering the morphological components of grain size, chemical and water content, organic material, and soil temperatures [equations (26) and (27) — all equation numbers refer to I. Basic Theory]. The rate of decomposition

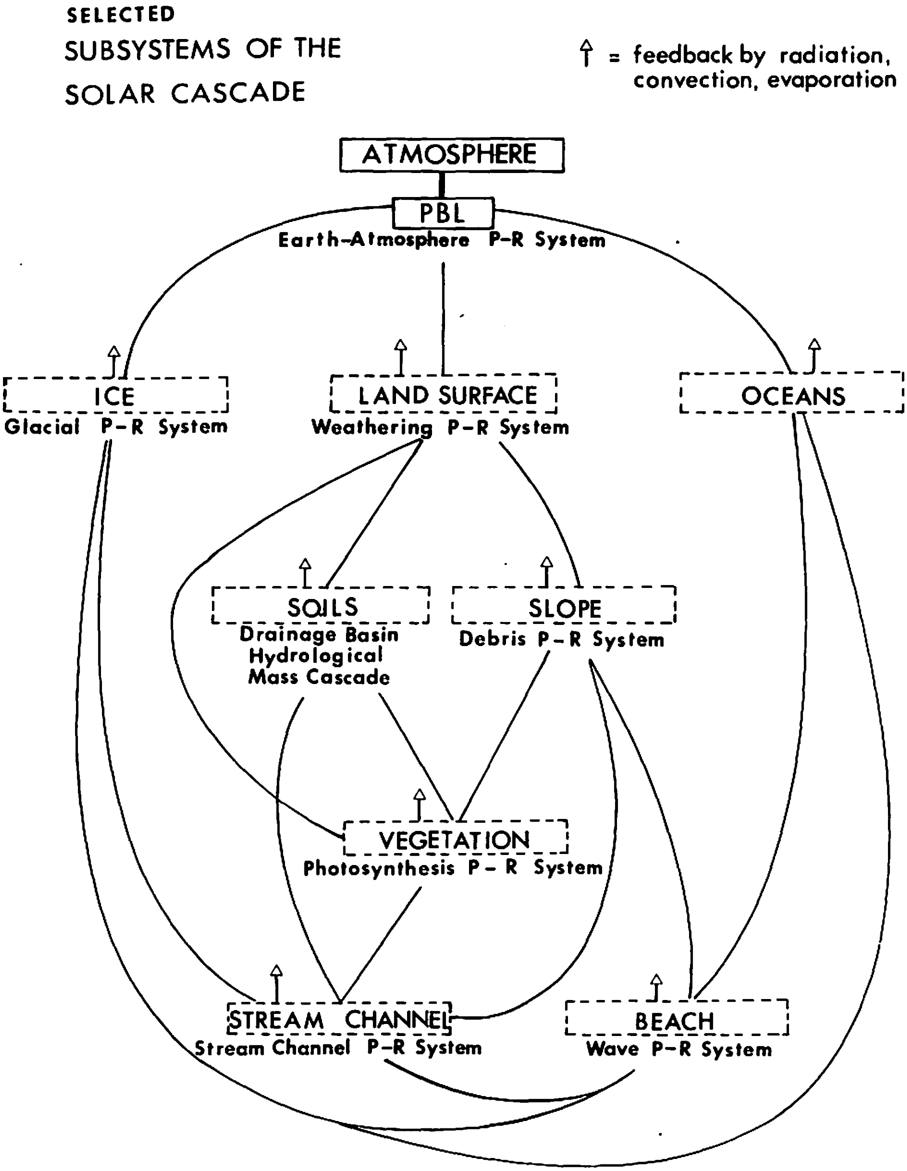
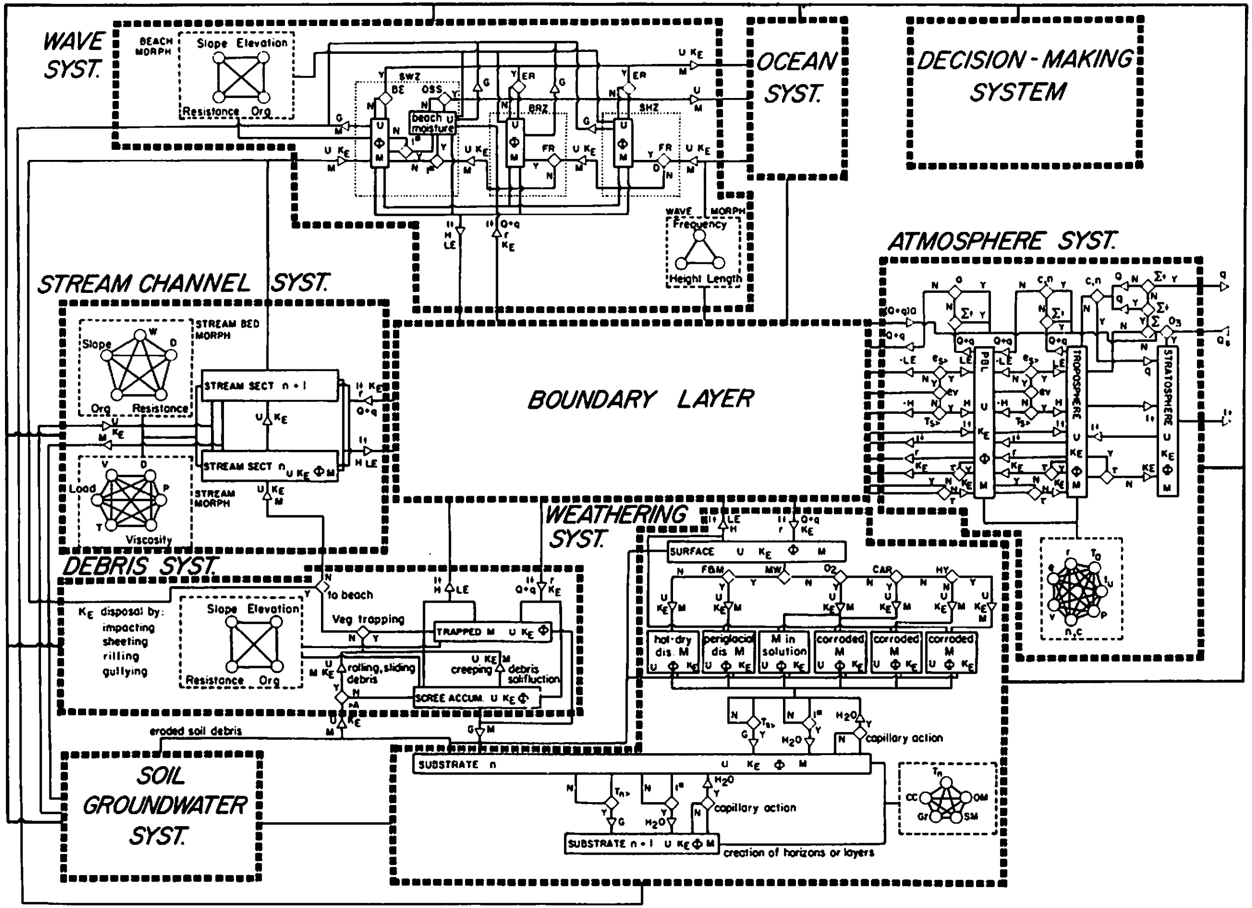


Fig. 6: Selected subsystems of the solar cascade.



Drainage Basin Process-Response System

Fig. 7: Drainage basin process-response system.
See Fig. 5 and Notations for explanations.

depends on the chemical character of the rock, water, and substrate temperatures. The various soil or substrate temperatures are determined by the soil heat flux G (changing internal energy U) which is a result of the diurnal and seasonal fluctuations of energy inputs from the atmosphere system. Physically, an increase in soil temperature causes decreases in air flow through the soil and water holding capacity because of an increase in the viscosity of soil moisture and surface tension. The same effect causes increases in the translocation of soluble salts, solvent action of water, decomposition of organic material and, generally, chemical weathering. Biologically, soil temperatures also influence soil micro-organisms, plant roots, plant diseases, and the germination of seeds. Mechanical weathering is also partially a function of soil and surface temperature and moisture content.[20)]

All this results in the formation of horizons or layers in the soil and regolith. Simplifications entail the regulators which decide between only a few possible weathering processes (disintegration by mechanical weathering and chemical weathering by oxidation, carbonation, hydration, and solution). This may seem gross to the purist, but detail can always be added to any desired degree.

The decision-making system could interfere in the weathering cascade, for instance, with the introduction of pollution in the case of corrosion, and maybe eventually even with artificial climatic changes in aspects of mechanical weathering (e. g., freezing and melting frequencies, aridity). The forcing of energy, mass, and momentum on the various storages will change the interrelations of the components of each of the morphological systems associated with a particular store. The top layer (or surface) has a feedback via reradiation, convection, and latent heat flux to the PBL. Given sufficient time, and relatively little removal of matter, the output of the system could result in a soil system (not elaborated in graph). Of more immediate interest, part of the output can also enter a debris system which is essentially a transportation system or surface.

The next logical step is to follow the debris created by the weathering system. This slope system (debris system) is characterized by the conversion of potential energy into kinetic energy K_E and frictional heating [equation (47)]. The debris (or overland flow) system is the link between the weathering system and the stream channel or wave systems. Eroded soil also may enter the system. As a critical slope angle A is exceeded, coarse material especially will roll and slide downhill passing through the upper scree system. This would include materials from landsliding and unloading.[21)] The finer material would have a chance to be stored in scree accumulation. Part of the kinetic energy K_E of water is disposed by impacting (in the case of precipitation), sheeting, rilling, gullying, and seepage to the groundwater, depending on the imperviousness of the slope substrate. The frictional heating resulting from the erosional action of this mass movement is converted into reradiation $I\uparrow$, convection H, latent heat flux LE, and conduction G. These latter fluxes are several magnitudes below those caused by the atmosphere system.

The scree accumulation store is usually only temporary, since debris will creep downhill (including the effect of solifluction). Thus, both the rolling and sliding debris will become input to the lower scree subsystem. Here, in addition to the above mentioned accumulation possibility (omitted from graph), vegetation trapping becomes important. The regulators for slope angle and vegetation-trapping are especially susceptible to interference by man. Vegetation-trapping is also influenced by input from the atmosphere system (solar radiation $Q + q$, counterradiation $I\downarrow$, precipitation r) or a separate photosynthesis process-response system. The downslope cascading of energy, mass, and momentum and the morphological components of slope, elevation, and organization are reciprocally being modified. Resistance is also modified by a weathering system operating on the slope itself (not shown). Finally, the output of the debris system becomes the input for the stream channel or wave system (if the slope ends at a beach). As for all watershed considerations, deterministic and parametric models generally make use of versions of the equation of continuity [equations (21), (23), or for incompressible fluids, equation (24)] and momentum [equations (35), (37), (41), and (42)]. Other considerations deal with shearing and normal stresses [equations (13), (38), (39), (40), (47) and (48)] and conduction of heat into the ground [equation (9)].[22]

In the stream channel system (much simplified), the flows of energy (U, K_E), water, debris, and biochemicals through the stream channel results in energy dissipation [internal energy U is influenced by frictional heating — equation (49) or (50) — from the momentum input of mass motion but, most importantly, by input from the atmosphere system] and changes in the components of the stream morphological and the stream bed morphological systems. Since there are many possible additions and subtractions of energy, mass, and momentum along the course of a stream because of precipitation r, evaporation LE, bank-caving, erosion, seepage, point-bar formation, etc., the system has to be subdivided into a suitable number of subsystems. Thus, each subsystem also contains its applicable morphological system. As far as the transporting medium (water) is concerned, the inputs, throughputs, and outputs of energy, mass, and momentum modify the components of each of the stream morphological systems in regard to stream velocity [equation (41)], discharge [equation (21), (23) or (24)], pressure [equation (32)], temperature [equation (49) or (50)], viscosity [resistance to flow because of fluid properties — equation (40)], and the dissolved, suspended, and bed loads.[23] There are also reciprocal connections between the latter and the various possible streambed systems [components include width, depth, slope, organization (e. g., meandering), and resistance], as well as the forcing of the cascade systems. Resistance can be interpreted in terms of macro-roughness (e. g., a meander bend) or micro-roughness (e. g., resistance of debris in the channel and along the channel perimeter).[24] Along the entire course, energy (K_E) and mass (water) can be exchanged between the stream subsystems and their respective groundwater systems. At any point, man's decision-making (especially by urbanization and engineering modifications of channels) can be a powerful influence. For instance, by installation of storm sewers and the increase of impervious pavements, the lag time between precipitation and runoff can be shortened, resulting in an increase in flooding.[25]

Most commonly, the final sink of the energy, mass, and momentum output of the stream channel system is the wave system. In arid regions where internal drainage exists, the stream system may output into a playa. Whatever may be the place of output, the point of maximum entropy of the river can change under the forcing from the tectonic cascade by altering its potential energy Φ, establishing new base levels.

Although occupying only a relatively small portion of the earth's area, the uniqueness of shorelines lie in their position of contact between the interfaces of land, ocean, and atmosphere. The larger coastal zone itself (in terms of geological times scales) is mainly determined by the tectonic energy cascade (resulting, for instance, in trailing edge and collision edge coastal zones), whereas the shore zone, primarily the interface between the stream channel system and the interaction of waves, wave-induced currents and wind currents, is subjected to the short-term, cyclic forcing of the ocean and atmosphere.[26]Here, shore processes begin the mixing, sorting, and transportation of sediments and mass runoff from the land, accomplished by a complex system of costal circulation cells.[27]

The wave system receives inputs from the stream channel (including debris from sea cliffs), ocean, and atmosphere system. As wind blows across the water, a momentum exchange occurs [equation (40)] between the kinetic energy K_E of the air flow and the water surface. This exchange results in wave morphological features of wave height, length, and frequency.[28] The wave morphological system is also influenced by tides produced by the gravitational attraction of the moon and sun (for convenience, assigned to the atmosphere system) acting on the mass of the ocean. The shore zone is generalized into the subsystems of the shoaling zone SHZ (beginning of critical depth of bottom interference for waves), breaker zone BRZ (waves begin to increase in height and shorten horizontally, finally toppling), and shallow-water swash zone SWZ where the back-and-forth motion of waves produces major stresses on the bottom [equations (13), (29), (38), (39)], setting sand in motion.

For instance, mass (and its characteristic energies of K_E and U) arriving in the form of water or sediments can be partially allocated to storage (via frictional loss FR and deposit D) or transported further shoreward to the breaker or swash zone. Storage has outputs of energy ($I\uparrow$, H, LE to the atmospheric system; G to the substrate), and mass (E to the atmospheric system; erosion to the ocean system). As in all the subsystems, the respective beach morphological system is reciprocally linked and modified in its generalized components of slope, elevation, resistance, and organization. From the swash zone, receiving inputs from both the stream channel system and the breaker zone, offshore seepage of beach moisture can occur.[29] This "seepage" could also be visualized as forming an advancing salt water lens, extending inland if groundwater reserves have been depleted.[30]

In the wave system the flow of interference from man's decision-making system can be enormous. Beach systems experience the impact of waste discharge, thermal and radioactive pollution, dredging, coastal construction, mining, and poaching.[31] This intervention appears to take the interrelated forms of the impact of the numbers of people, the pollution, and the alterations in the ecology of plants and animals and the sources of sediments for the steady state conditions of beaches. The beach system is another good example where single-remedy planning and technology has to be replaced by a physical-human process-response system in order to perceive and better optimize the workings and mutual interactions of the whole system. To achieve this, a rigorous process-response model has to be linked with a decision-making model derived in the social sciences. Subjecting such a hybrid model to sensitivity analyses and simulations of the activities of man or possible planning strategies is enormously less costly than solutions based on pure empiricism and trial and error.

The unifying nature of the concepts of the exchanges of energy, mass, and momentum and their associated process-response systems can also be demonstrated for conditions outwardly quite different from those discussed so far.

Urban Process-Response System

That all physical phenomena appearing in geography are creatures of the same basic concepts of forces becomes increasingly apparent in another rather special and very complex system which models man in the setting of an urban landscape (Fig. 8). The urban process-response system, representing the integration of many "field", can be visualized as "relevance par excellence" for geographers, since it touches upon or encompasses some of the major human concerns in the latter half of the 20th century: energy, food, and the quality of life. In addition to its complex decision-making system (containing elements of urban, economic, transportation, and agricultural geography), this urban system is generalized into six subsystems: man (related, for instance, to the comfort, health, clothing of man — even animal production, since a human energy budget is similar to most mammalian equivalents), atmosphere (e. g., related to climatic changes, diffusion and circulation of air pollution, crop diseases), building (e. g., urban planning and architecture, heating and cooling, sources of air pollution, food storage), street (e. g., transportation and commerce), park (e. g., canopy systems, crop and primary production), and soil-water (e. g., water resources, soil alterations). Each subsystem is thought to be an abstraction for all possible types, configurations, and multiple locations.

For the sake of clarity, all systems have been very much simplified. This comment applies especially to the atmospheric section, where numerical model-

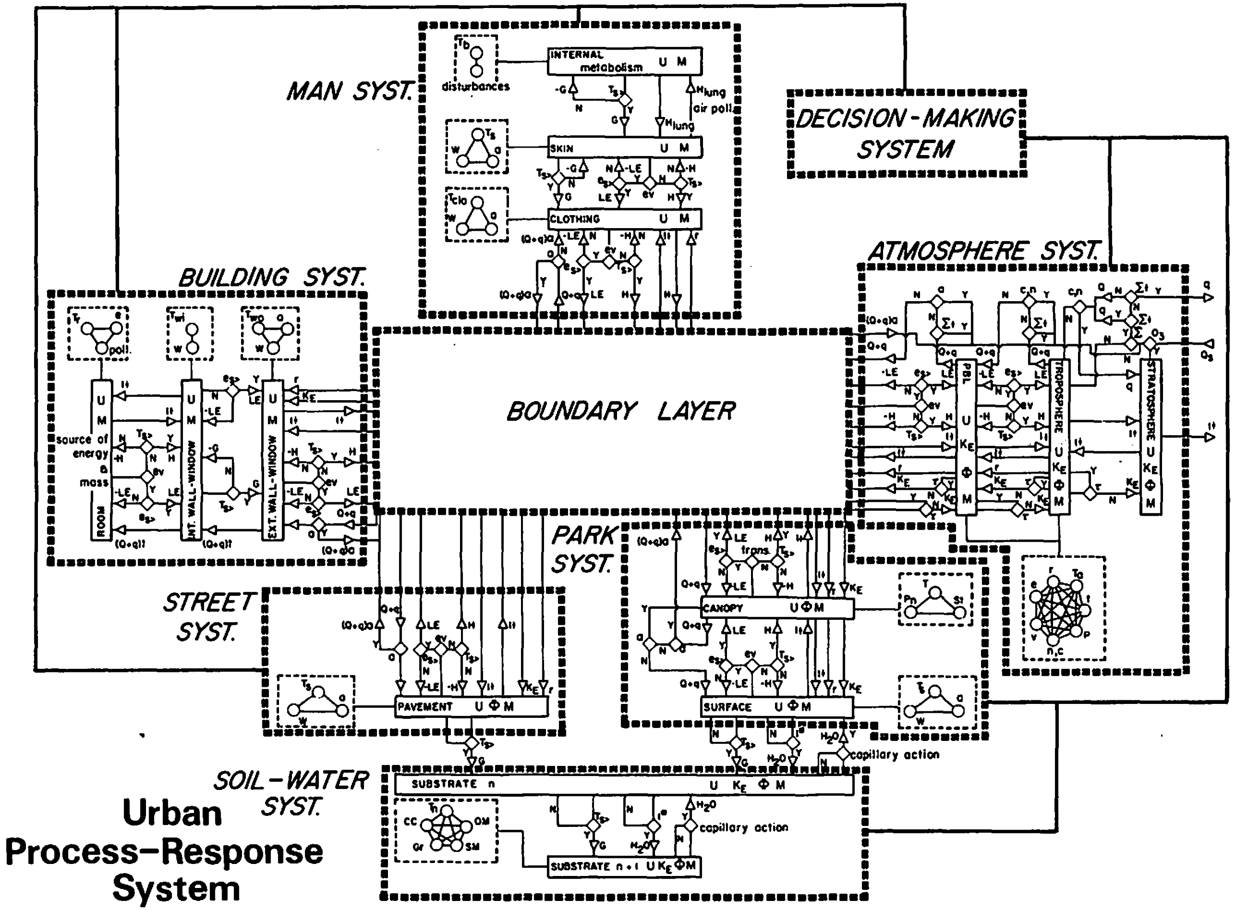


Fig. 8: Urban process-response system (from TERJUNG and O'ROURKE, op. cit., [33]). See Fig. 5 and Notations for explanations. $T_{s>}$ = surface temperature of a layer is greater than the temperature of layer n + 1 ($T_n > T_{n+1}$); $e_{s>}$ = surface vapor pressure of a layer is greater than the vapor pressure of layer n + 1 ($e_n > e_{n+1}$).

ling is probably most advanced.[32] For instance, the reader should visualize many additional storage layers between the stratosphere, troposphere, and PBL. Also, the atmosphere is shown as a closed system, omitting advection of energy, mass, momentum from the x and y directions. To varying degrees this also applies to the other systems. In actual models this can be incorporated easily.[33]

Air temperature T_a, pressure P, precipitation r, humidity e, wind speed v, cloud type and amount c, n, and turbidity t_u have long been the staple of traditional climatology. These variables actually constitute a complex morphological system which is being forced and determined by the cascading of energy, mass, and momentum. In fact, if we ignore for the urban system the events occurring on the tectonic time scale, the "initial" input and trigger for all the subsequent complexities begin with the solar energy arriving at the top of the stratosphere Q_S (right side of graph). Absorption (e. g., by ozone 0_3 in the atmosphere, water vapor, etc. in the troposphere and PBL), scatteringΣ, and reflection (c, n, a) take their toll as this energy cycles and recycles through the earth-atmosphere. Eventually, after having travelled in its various forms through the other subsystems, this energy is emitted as planetary reradiation $I\uparrow$ and reflection q. The atmospheric morphological system is only a by-product of this drama.

The man and building system are in many respects similar in their response to the solar cascade. Both can be generalized into a series of layers (resistors?) beginning with an outer perimeter (exterior clothing surface or building wall/window) and terminating in an internal storage. In both cases, this is not just a passive store, but it is also an internal source of energy and mass. For man, this source is his metabolism (a function of food intake, work, and degree of "disturbance"), whereas the building analogue is the input of artificial heating, cooling, moisture, particulates, and gases. Thus the abstract "room" can be further extended, for example, to factories. Each layer interval has its particular gradient (T_s› or e_s›) of energy and mass which regulates inputs and outputs between layers and, ultimately, between systems. For example, the building system could be one of the sources of pollution which reaches the boundary layer and PBL, ultimately affecting all systems (e. g., man's intake of pollutants via pulmonary action H_{lung}).

At the outer clothing or skin surface, the relevant morphological components modified by internal energy U are clothing and skin temperature T_{clo}, T_s, clothing or skin albedo a, and the relative wetness W of the clothing or skin (also influencing a). The internal body temperature T_b is a result of environmental influences and the body's metabolism. Just as the walls of a building, the clothing layers act as barriers to the diffusion of mass (e. g., moisture E) and energy (conduction G, latent heat flux LE).[34]

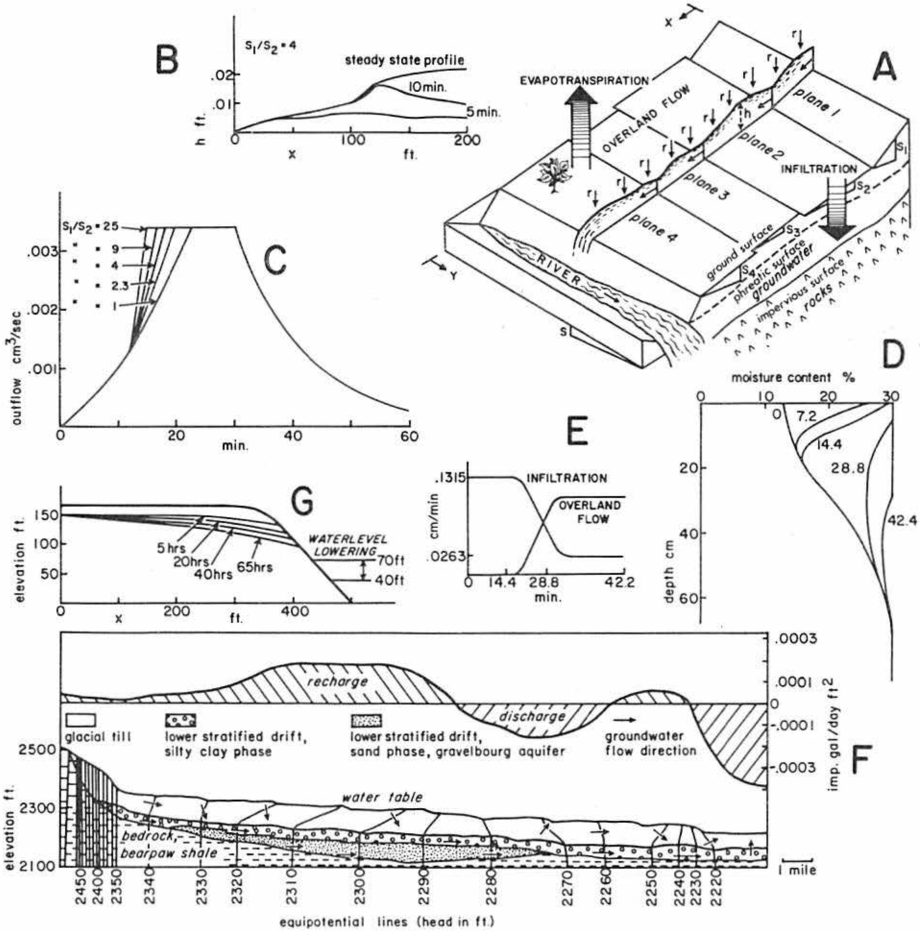
The street and the park system share a common substrate for convenience. The former is the simplest of all systems and has often been the focus of research in urban climatology. Figure 8 suggests that such research might be too isolated to infer much about urban process-response systems. The canopy part (including a photosynthesis system) of the park system is much generalized by using only one canopy storage. Actual canopy models use many such layers.[35] For this example, the morphological responses of the foliage to energy, mass, and momentum cascades is simplified to net photosynthesis P, leaf temperature T, and stomatal resistance St. This latter component will largely determine the diffusion (via transpiration) of water vapor e into the boundary layer. Partially because of the latent heat flux LE, parks are "cool islands" in cities. Model simulation of the location strategy for parks can determine the optimum siting without the great expense accompanying current trial-and-error methods.

The surface response of the street and park system is similar, except for the type of cover. The internal energy U determines surface temperature T_S and influences albedo a and wetness W. The soil-water system exchanges energy (conduction G) and mass (infiltration I* or capillary action) with the surface. This forcing is reflected in changes of soil (or water) temperatures T_n, soil moisture SM, chemical content CC, organic material OM (decaying plants, etc.), and grain size GR (texture).

All urban systems, except for the soil-water and the atmospheric system, experience different shading and consequent radiation regimes which vary daily and seasonally in the x, y, and z directions of the urban landscape. View-factor algebra has to be used to solve such complex relations.[36] The chief goal of this research is the simultaneous solution of the transient three-dimensional, partial differential equations governing the urban boundary layer and the discussed subsystems (see section on conservation equations -I. Basic Theory). The reader is referred to several excellent reviews suitable for geographers who are interested in entering this promising field.[37] I believe nothing needs to be said in regard to the great importance of the workings of the urban decision-making system. After all, most of us experience its effects in our daily lives.

Selected Examples of Process-Response Modeling

In order to show geographers the potential and utility of process-response modeling, a series of examples is selected. This is not an easy task, since each case study represents research efforts of at least article-length. To properly understand this research, the reader is urged to read the original works and not to depend completely on the necessarily superficial treatment given here. The selection of examples is arbitrary and is dictated by my own competence and my perception of what geographers might be interested in. A problem of finding "good" examples exists since, in spite of the rapidly growing literature, process-response modeling is still in its infancy and many workers pursue goals which might not interest geographers. This does not invalidate the approach. In the future, it will be the task of the geographer to utilize the rich harvest of the methodology inherent



B
$S_1/S_2 = 4$
steady state profile
10min.
5min.
h ft.
x
ft.
A
EVAPOTRANSPIRATION
OVERLAND FLOW
plane 1
plane 2
plane 3
plane 4
INFILTRATION
RIVER
ground surface
phreatic surface
groundwater
impervious surface
rocks
C
$S_1/S_2 = 25$
outflow cm^3/sec
min.
D
moisture content %
depth cm
E
INFILTRATION
OVERLAND FLOW
cm/min
min.
G
elevation ft.
5hrs
20hrs
40hrs
65hrs
WATERLEVEL LOWERING
70ft
40ft
recharge
discharge
imp. gal/day ft^2
F
glacial till
lower stratified drift, silty clay phase
lower stratified drift, sand phase, gravelbourg aquifer
groundwater flow direction
water table
bedrock, bearpaw shale
elevation ft.
1 mile
equipotential lines (head in ft.)

Fig. 9: Selected modeling examples of the drainage basin process-response system.

A. A hydrological model consisting of a 4-plane cascade receiving lateral inflow and discharging into a channel segment (modified from KIBLER und WOOLHISER, op. cit. [22]). A generalized groundwater system has been added. S = slope angle, r = precipitation, h = local depth of water surface.

B. Finite element solution of the equation of continuity (24) and a two-dimensional form of the NAVIER-STOKES equation (42) for the instantaneous water surface profiles when $S_1/S_2 = 4$ (modified from TAYLOR, AL-MASHIDANI and DAVIS, op. cit., [25]). Rainfall = 0.75 in/hr. This domain (length = 200 ft; 61 m) was divided into two equal parts simulating a simple cascade (e. g., plane 1 and plane 2, Fig. 9A). The slope of the upstream domain was made progressively steeper for each computation (see also Fig. 9C). The roughness was assumed constant over the whole domain. Note the development of a shock-wave producing an abrupt increase in flow depth. Such.rises occur naturally whenever overland slope decreases abruptly or whenever surface roughness increases are sudden.

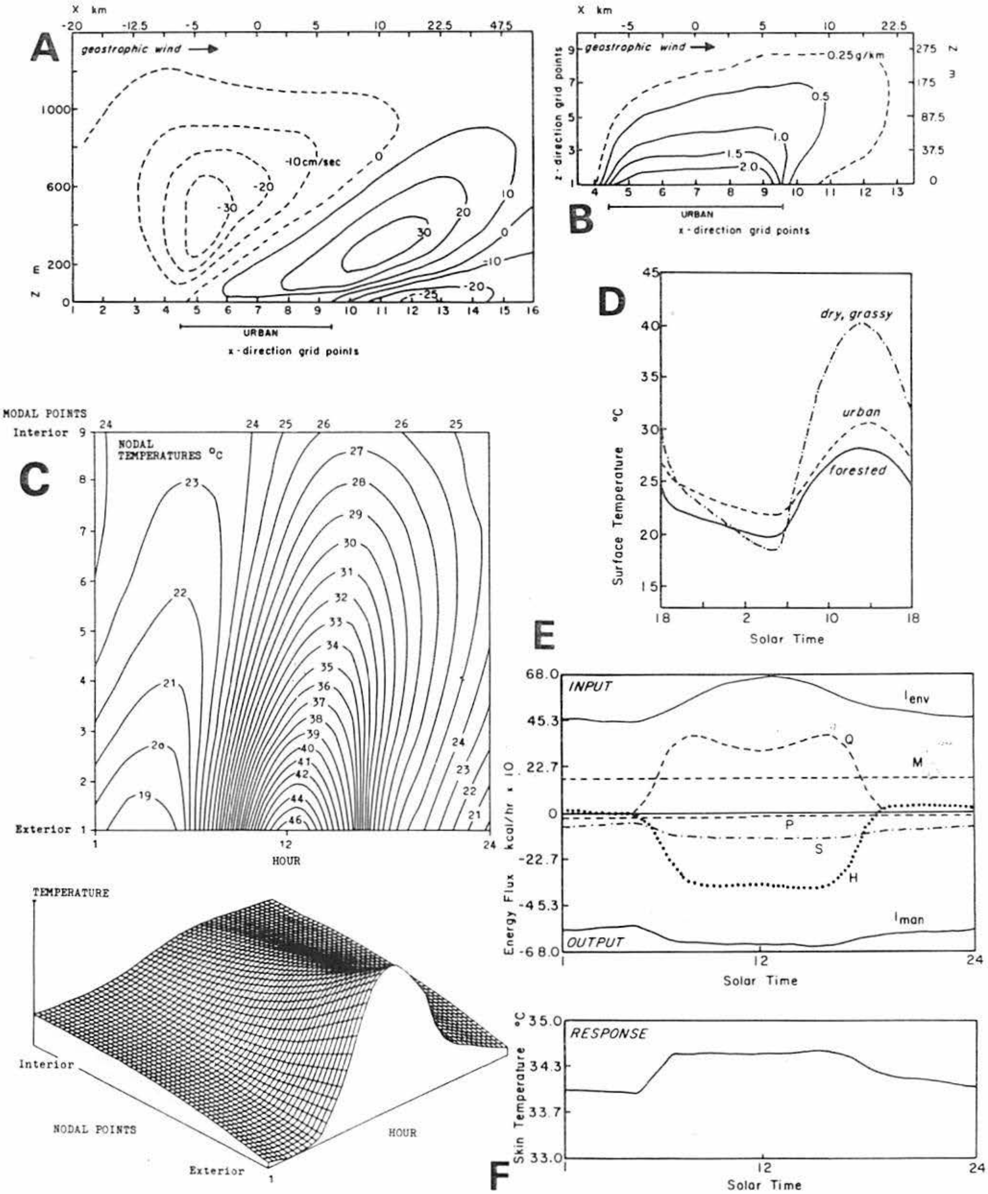
C. Outflow hydrographs showing influence of shocks or changing slope rerelations (S_1/S_2). Conditions were the same as used in Fig. 9B (same reference).

D. Numerical solution to a model of one-dimensional vertical infiltration into a recharging groundwater flow system utilizing the one-dimensional version of the continuity equation, (21) and (24) (modified from FREEZE and HARLAN , op. cit., [10]). Profiles are labeled with the number of minutes elapsed since the beginning of the run. Rainfall intensity (0.1315 cm/min) caused saturation at the surface about 20 minutes after the start of the rain. Ponded water then resulted until the maximum depth of ponding (10 cm in this case) was reached. During this time, a saturated layer of increasing thickness developed at the surface. Between times 28.8 and 42.4 minutes, the water table rose from a depth of 92 cm to 86 cm. After 42.4 minutes of infiltration the column was saturated (30%) over almost its full length.

E. Plot of the rates of infiltration and overland flow versus time for the above example.

F. Two-dimensional flow pattern through the Gravelbourg aquifer, Sasketchewan, Canada as determined by a numerical solution [continuity equation (24)] of a mathematical model (modified from FREEZE and HARLAN, op. cit., [10]). If we assume the processes in Fig. 9D to be taking place below a given surface node, this model combines many such nodal points into an integrated hydrologic model with four geological formations. The equipotential lines are shown and the directions of groundwater flow are indicated by arrows. It is possible to analyze this flow system in order to calculate the natural basin yield and to determine the rate of recharge at any point on the water table. The recharge-discharge profile (upper portion of graph) indicates that the rate of flux across the water table varies widely geographically.

G. Three-dimensional, transient flow [parameterization of equation (24)] of a moving phreatic surface as determined by numerical modeling (modified from FRANCE, op. cit., [25]). The volume defining the flow domain was subdivided into a number of cubic isoparametric elements (six in this case) interconnected at a discrete number of nodes. Since the phreatic surface is composed of element boundaries, the upper face of each of these elements represents a portion of the moving boundary. This example represents part of a curved embankment along which a river flows, initially at a constant depth of 100 ft (30.5 m). It was first required to locate the steady state phreatic surface corresponding to this particular water level. The level of the river was then assumed to vary in depth along its embankment from 100 ft at one profile to 70 ft (21.3 m) at another and fall at a rate of 5 ft/hr (1.5 m/hr) until it is 70 ft and 40 ft (12.2 m) respectively (only the first profile is shown). Thus the location of the phreatic surface had to be traced while the river declined. In this example the following conditions were analyzed: (a) an irregularr flow regime; (b) a sloping downstream face; (c) an inclined impervious bed sloping in both directions; and (d) a phreatic surface which cannot be predicted with any certainty. Twenty time increments of five hour duration were specified, but steady state was attained after sixty-five hours.


A
geostrophic wind
-10cm/sec
URBAN
x-direction grid points
X km
z m
B
geostrophic wind
0.25g/km
URBAN
x-direction grid points
z-direction grid points
C
NODAL POINTS
Interior
Exterior
NODAL TEMPERATURES °C
HOUR
TEMPERATURE
D
dry, grassy
urban
forested
Surface Temperature °C
Solar Time
E
INPUT
OUTPUT
I_{env}
I_{man}
Energy Flux kcal/hr x 10
Solar Time
F
RESPONSE
Skin Temperature °C
Solar Time

in that literature for his own goals. As a demonstration of the generality and universal application of the presented conservation equations (I. Baisc Theory), I tried to be as diversified as possible by choosing from several widely different topics.

Fig. 10:Selected modeling examples of the urban process-response system.

A. Distribution of horizontal wind speed after six hours (at 2400 hrs) of simulated time for the flow over a rough, warm city (modified from BORNSTEIN, op. cit.,[33]). This pattern was created by the solution of a two-dimensional, transient numerical model using versions of the equations of motion (37), continuity (24) and energy (50). The model consisted of a lower constant-flux layer and an upper transition layer. This simulation attempted to reproduce the temperature and wind effects on the structure of the urban boundary layer. Values represent the deviation from values at the upwind boundary (geostrophic wind speed = 3 m/sec, urban roughness = 3 m, rural roughness = 0.5 m). The graph shows a region of decreased wind speeds, as compared to those at the upwind rural boundary and a region of increased speeds downwind of the city.

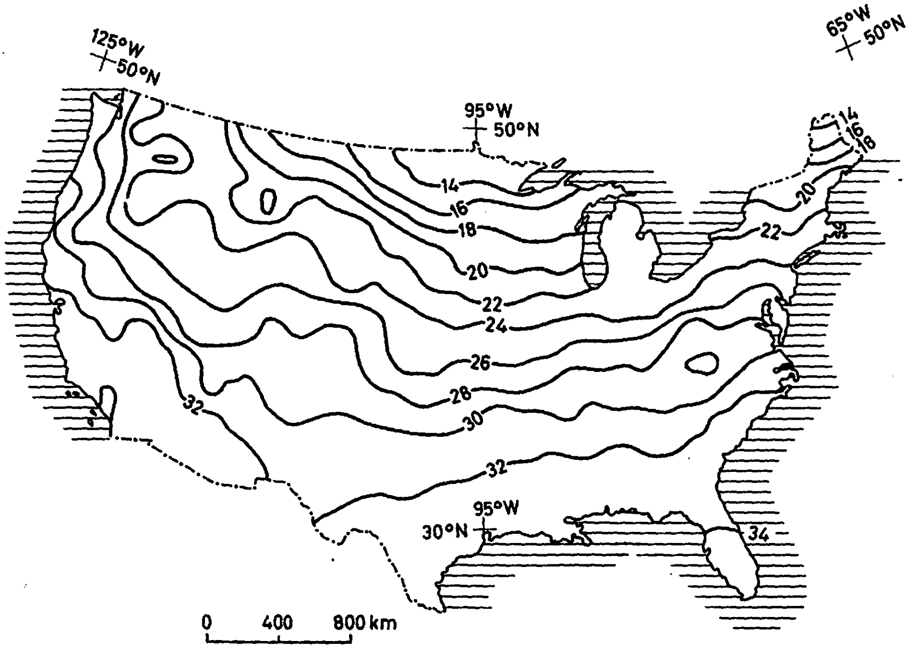
B. Distribution of the perturbation (deviation) specific humidity after twelve hours (at 0600 hrs) of simulated time for the flow over a warm, rough, wet city (modified from BORNSTEIN and TAM, op. cit.,[10]). The numerical model was the same as Fig. 10A, except for the inclusion of a continuity equation (21) for water vapor and the choice of magnitude of the time step used in integration. Values represent the deviation from those at the upwind boundary. This simulation attempted to reproduce the effects of an anthropogenic source of moisture on the structure of the urban boundary layer. The excess moisture thus placed into the urban atmosphere was advected and diffused vertically and horizontally according to equation (21).

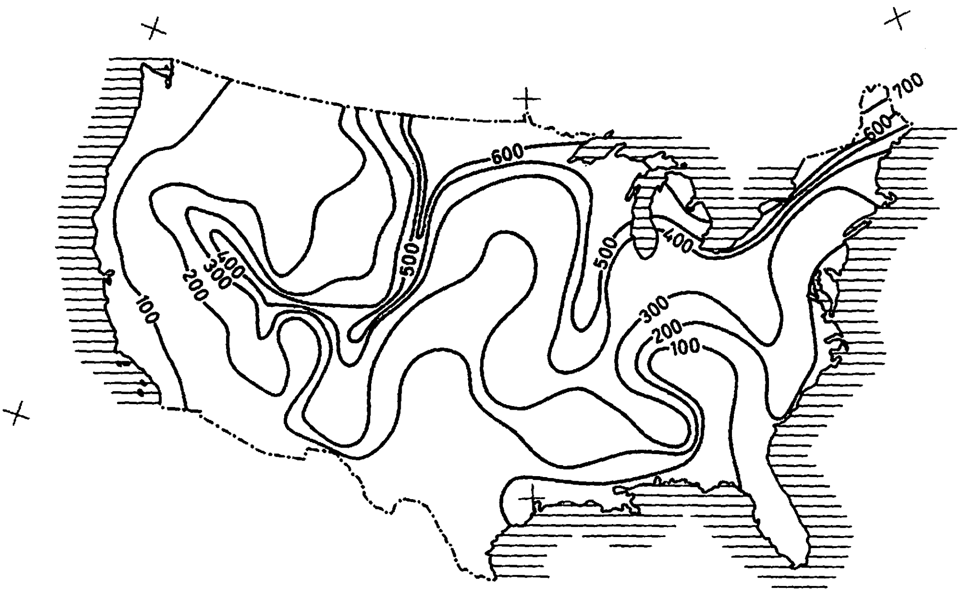
C. The diurnal distribution of temperatures (summer) inside a concrete roof (°C). (TERJUNG, LOUIE and O'ROURKE, unpublished work). The temperature field was created by a one-dimensional, transient interface energy budget model utilizing aspects of the internal energy equation (49). The inside of the wall was subdivided into nine nodal points (y-axis). The interior room temperature was kept at a constant comfort temperature of 75°F (23.9°C), whereas the external air temperature regime ranged from 32°C to 18.5°C. Latitude = 34°N, climate = Mediterranean. The temperature field depicts the time lag in energy flow in or out of a typical building [conduction equation (9)]. This type of pattern and the influence of street canyon geometry are major causes of the urban heat structure.

D. Comparison of diurnal surface temperatures for an urban, forested, and dry, grassy plain (modified from DIETERLE, op. cit.,[33]). The model is basically the same as the one used in Fig. 10A, B, except that the previous model was simplified to one dimension and modified for the surface energy balance [equation (49)]. The simulation shows that the surface temperature wave with the largest amplitude is that of the dry, grassy plain. The urban heat island is confined to the hours between midnight and sunrise. This model was an idealization, in that the urban surface was considered to be flat (not the case for Fig. 10C) and describable by constant thermal and aerodynamic roughness characteristics.

E. Diurnal distribution of the input-output components (cascading system) of the energy and moisture budget of man in Los Angeles during July (modified from BURT, op. cit.,[34]). A one-dimensional, steady state model was used to describe the ways a human being exchanges energy and mass with his surroundings. Aspects of the internal energy equation (49) were used for model construction I_{env} = environmental longwave radiation, Q = absorbed solar radiation by man, M = metabolic heat production, P = respiratory heat flux, S = perspiratory heat flux, H = human convective heat flux, I_{man} = human longwave radiation.

F. Diurnal distribution of the response (physical process-response system) to the cascade depicted in Fig. 10E. There is a day-night dichotomy in comfort conditions. At sunrise skin temperature increases rapidly, then levels off within an hour or two. Conditions remain stable through the daylight hours, but at sunset the skin temperature begins to decrease, finally reaching minimum values just before sunrise. The cause for this behavior is shown in the incoming and outgoing energies of Fig. 10E.


125°W
50°N
95°W
50°N
65°W
50°N
14
16
18
20
22
24
26
28
30
32
34
95°W
30°N
0
400
800 km


700
600
500
400
300
200
100

Drainage Basin Process-Response System

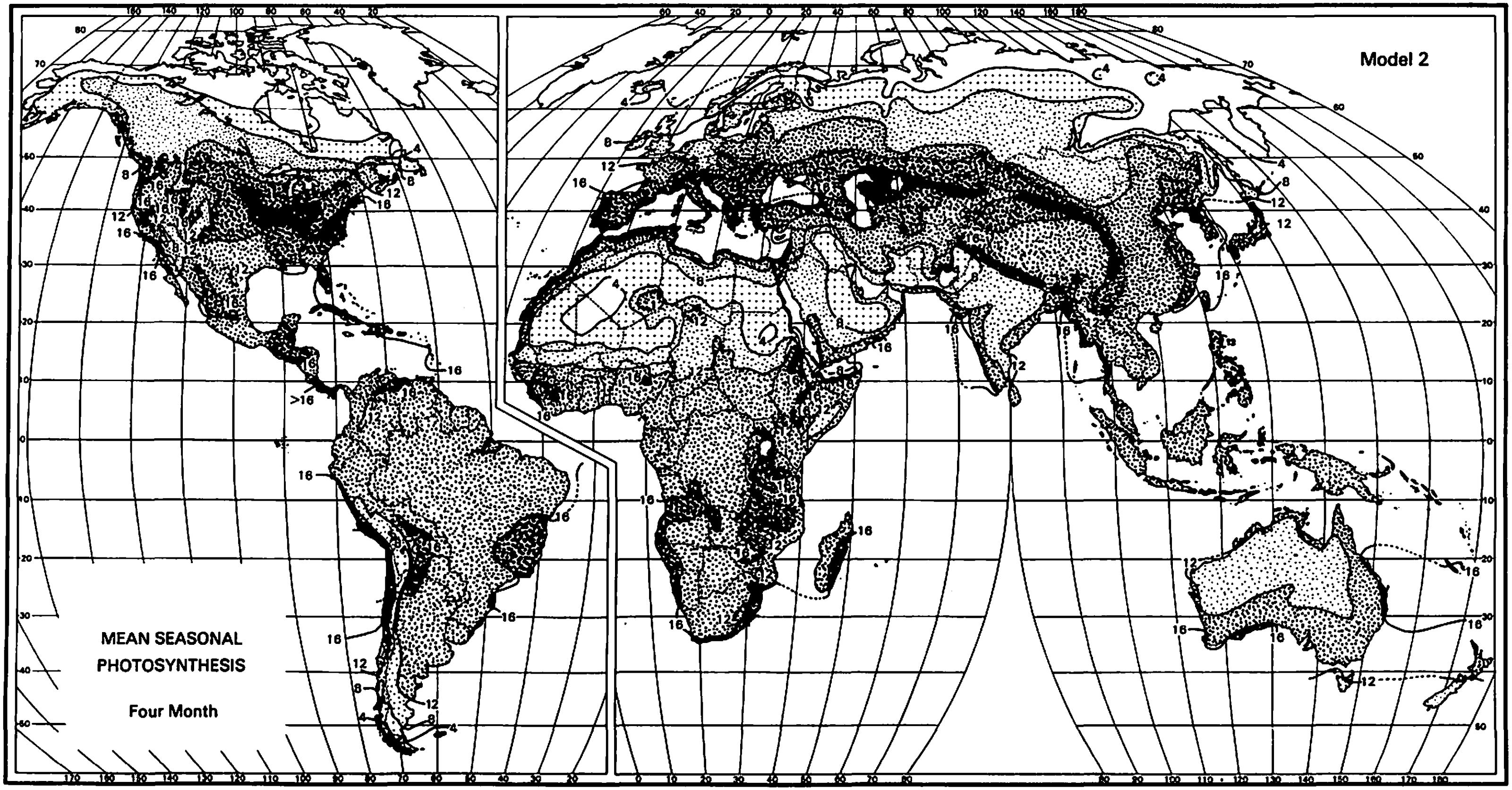
Compared to the following urban process-response system, research in this basically geomorphic system has bareley begun to utilize numerical modeling. This modeling appears most advanced in groundwater systems and least sophisticated in stream channel (including overland flow) systems. The momentum and continuity equations are generally the guiding principles in this research.

A common approach is to "linearize" the landscape above and below the surface into a series of planes or domains of different slope angles (Fig. 9A). The closer the spacing of the resulting finite grid or element system, the better reality will be mimicked. For instance, the cause and effect of changing slope angles in overland flow or stream flow have been simulated (Fig. 9B, C). Vertical infiltration of mass (especially water) has frequently been examined by numerical modeling (Fig. 9D, E). More sophisticated models are beginning to depict multidimensional structures and larger areas (Fig. 9F). The three-dimensional effect of lowering water levels on phreatic surfaces, stream flow and stream water level has led to results of potential interest to geographers (Fig. 9G). Most of the insights gained by the analytical, cause and effect, results of the presented cases would not have been revealed by convential methods, relying heavily on field work or stochastic modeling. Only a very expensive and time consuming program of data collection might have gained similar results. Even then, probably, the same level of generality would not have been achieved, and would be lacking the benefit of the knowledge of internal workings of the system.

Urban Process-Response System

Within this framework, the atmosphere system has been examined in the most detail by numerical modeling, utilizing nearly the whole complement of the parameterized conservation equations for energy, mass, and momentum. The modeling of man, building and park (canopy or photosynthesis) systems has usually utilized only one-dimensional, steady state versions of the internal energy equation, omitting feedback to the atmospheric temperature, wind, and moisture fields.

Fig. 11: Examples of the man and building system in the greater framework of the urban process-response system. Top map: Mean skin temperature (°C) for daytime in January (modified from BURT, op. cit.,[34]). Maps of skin temperature can be used to analyze patterns of comfort since it correlates well with the subjective verbal expression of comfort, it has a readily understood physical interpretation, and it may be used directly in an energy budget equation to standardize the observed environment to some reference environment. Bottom map: Possible annual heating-cooling cost reduction (in Dollars) upon decreased window size and added insulation (modified from LEIBS, op. cit.,[34]). The one-dimensional, transient model, utilizing a version of the internal energy equation (49), computed the amount of energy necessary to keep the indoor temperature at a comfort level of 75°F (23.9°). Cost was based on the cost of electricity for a room on the top floor in the northeast corner of an office building.



Model 2
MEAN SEASONAL
PHOTOSYNTHESIS
Four Month

The urban boundary layer has been simulated by increasingly sophisticated techniques with results which begin to make us understand the behavior of the air above and beyond a city (Fig. 10A, B, E). This aspect of the application of process-response models to the urban landscape could be termed the "external" view and macroscopic, where a city is simulated as a warm, rough, wet plate. Another consideration is the "internal" or microscopic view, where the city is subdivided into street canyons on a block-by-block basis and where energy fluxes are followed in and out of buildings (Fig. 10C, D). The former view is important, for instance, to gain insight into urban circulation and air pollution patterns, whereas the latter is of potential importance to architectural design, urban planning, and the conservation of fuel used for heating and cooling. The ideal model would contain both approaches.

Cities without man are meaningless. Thus, an addition to the urban system would be a man subsystem (Fig. 10F, G). Here, man can be modeled in a street canyon environment or an indoor setting. This can be carried further geographically, where the modeling of man's comfort can lead to estimates of energy (or money) saved if architects observed certain precautions in siting and planning buildings (Fig. 11).

Another application of process-response modeling to the "park" system is in photosynthesis-plant models (Fig. 12). The importance of such endeavors in regard to the tenuous world food situation needs no discussion. Again, as in the case of the drainage basin system, classical empirical or stochastic studies would be either impossible because of the excessive money or time requirements or a physical impossibility. Imagine, for instance, setting up instruments alongside skyscrapers and through a city's busy street canyons.

Final Remarks

An abbreviated account is given of the importance to physical and general geography of the inclusion of process-response systems, simulating the exchan-

Fig. 12: Mean seasonal potential photosynthesis for four summer months for wheat-like and rice-like crop plants (10 mg CO_2/dm^2 day) (TERJUNG, LOUIE and O'ROURKE, op. cit.,[35]). The heavily stippled pattern without isoline designation indicates photosynthesis of › 175 mg CO_2/dm^2 day. This probable potential productivity pattern (prescribing no lack of soil water, fertilizer, pest and disease controls, advanced cultivation techniques, etc.) was created by the calculation of leaf temperature [via a one-dimensional, steady state version of the internal energy equation (49)] and the addition of a family of photosynthetic response curves as function of solar radiation and leaf temperatures. The map entailed the summing of the hourly solution for 1650 stations for four months, i. e., 160.000 sets of calculations. Models of this nature, being functions of climate alone, could aid in the determination of potential areas for agricultural production or better utilization of existing cultivated areas. Highest potential production appears to be in the middle latitudes (including its deserts), tropical highlands, and tropical and subtropical cool-current littorals. Lowest potential production is shown in the tropical and subtropical deserts.

ges of energy, mass, and momentum in the landscape envelope of relevance to mankind. Traditionally, quantitative methods in physical geography have been largely stochastic, viewing nature as chaotic and inscrutable in regard to cause and effect. In such a morphologically oriented analysis process is often ignored or only vaguely inferred, but the cascades of energy, mass, and momentum are linked reciprocally with the morphological components, resulting in process-response systems called "physical landscapes." It apperars that a greater concern for the application of the laws of physics and their numerical modeling will tend to unify the now diverse field of physical geography.

Because of space limitations and my own ignorances, many facets have been omitted or only superficially treated. I did not intend to, and could not presume to, present a substantive review. The discussed area is much too vast and interdisciplinary to make such an analysis possible at this time. I could only hope to point to a method of research and to show a way of teaching which should be made part of the existing body of our discipline.

This sketchy presentation is accompanied by a section (conservation equations) which attempts to familiarize the general geographer with a basic set of ideal equations, derived from first principles, which should determine the state of many morphological components observable in the physical environment of man. In most cases, because of present limited computer capabilities, this set of equations is often not usable in the presented form. But, in order to understand and appreciate the rational of the many versions and parameterizations of these equations occurring in this research, the reader first has to become familiar with these basic principles in order to be able to profitably read and assimilate this important literature.

Zusammenfassung

Physisch-geographische Studien erfordern zur Lösung der gestellten Forschungsaufgaben nicht immer bis ins letzte Detail gehende Untersuchungen oder umfassende Datensammlungen im Gelände. Bei der Analyse kausaler Zusammenhänge landschaftswirksamer Prozesse sollte man einer Gruppe von grundlegenden Prinzipien Aufmerksamkeit schenken, die auf die meisten Forschungsprobleme in der "physikalischen" Geographie anwendbar sind.

Nach Meinung des Autors muß Forschung und Lehre in der physischen Geographie unter Beachtung der physikalischen Gesetzmäßigkeiten wesentlich verbreitert werden, damit Process-Response-Modelle in sie einbezogen werden können. Eine verstärkte deterministische Richtung erhält viele ihrer Grundlagen durch die Anwendung des Ersten Gesetzes der Thermodynamik und Newtons Zweitem Gesetz. Numerische Modelle physischer Process-Response-Systeme zielen letzten Endes auf eine Einbeziehung sozialwirtschaftlicher Entscheidungssysteme hin. Dadurch erhält die physische Geographie eine größere Relevanz für die kulturwirtschaftlichen Richtungen unserer Disziplin und für die menschlichen Belange schlechthin.

Notes and References

1 Mass is defined as weight/gravity or by the relationship: density = mass/volume; so mass = density x volume. Momentum = mass x velocity (velocity = distance/time).

2 The general reader who is not interested in the systematic development of the guiding conservation equations, could omit the following section without seriously interrupting the flow of the presented ideas. For further details see also W.H. TERJUNG, "Climatology for Geographers," Annals, Assoc. Amer. Geogrs., Vol. 66 (1976), pp. 199-222.

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4 Work = force x distance in the direction of the force, $W \stackrel{d}{=} ML^2\theta^{-2}$ (θ = time). The rate of doing work = power P = force x velocity in the direction of the force, or P = (force x distance)/time, $P \stackrel{d}{=} ML^2\theta^{-3}$.

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15 A. VERRUIJT, "Theory of Groundwater Flow " (London, 1970).

16 V. YEVJEVICH, "Determinism and Stochasticity in Hydrology," Journal of Hydrology, 22 (1974), pp. 225-38. See also R.M. MAY, "Deterministic Models with Chaotic Dynamics," Nature, Vol. 256 (1975) pp. 165-166; G.B. KOLATA, "Cascading Bifurcations: The Mathematics of Chaos," Science, Vol. 189 (1975), pp. 984-86.

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Notations

Symbol	Explanation
A	critical slope angle
a	albedo; acceleration (NEWTON's Second Law)
BE	beach erosion
BEZ	breaker zone
C_x, C_y, C_z	components of CORIOLIS force ($\vec{C} = -2\vec{\Omega} \times \vec{V}$)
c	cloud type
CAR	carbonation
CC	chemical content
c_v	specific heat at constant volume
D	depth (stream channel system); deposit (wave system)
D/Dt	substantial derivative or derivative following the motion, $\frac{D}{Dt} = \frac{\partial}{\partial t} + v_x\frac{\partial}{\partial x} + v_y\frac{\partial}{\partial y} + v_z\frac{\partial}{\partial z}$
dis.	disintegrated
e	vapor pressure
ER	erosion
ev	evaporation
F&M	frequent freezing and melting
FR	frictional loss
G	conduction ($\vec{G}$ = conduction vector; $\vec{G} = G_x + G_y + G_z$)
Gr	grain size or soil texture
$\vec{g}$	three components of gravitational force per unit mass, $\vec{g} = g_x + g_y + g_z$
H	convection
H_{lung}	pulmonary action of lung
HY	hydration
I	infrared radiation
I*	infiltration
j_i	mass diffusion flux of species $\underline{i}$
K_E	kinetic or mechanical energy (associated with fluid motion, i.e., $K_E = \frac{1}{2}\rho v^2$ per unit volume)
k	conductivity
LE	latent heat flux ($\underline{E}$ = amount of evaporation; $\underline{L}$ = latent heat of vaporization
M	mass
MW	mechanical weathering
morph.	morphological system
n	cloud density (atmosphere system); any integer value

OM	organic material
Org.	organization
OSS	offshore seepage
O_2	oxidation
O_3	ozone
P	pressure
P_n	net photosynthesis
P_i	mass rate of production of species $\underline{i}$
poll.	pollution
$\vec{q}$	heat flux vector, $\vec{q} = q_x + q_y + q_z$
Q_v	volumetric heat source
Q_s	solar radiation on top of the atmosphere
Q + q	global radiation (direct and diffuse)
R	gas constant
r	precipitation
SHZ	shoaling zone
St	stomatal resistance
SWZ	swash zone
T	temperature
t	time
T_a	air temperature
T_b	internal body temperature
T_{clo}	clothing temperature
T_r	room temperature
T_{wo}, T_{wi}	outside and inside wall temperature
t_u	turbidity
trans.	transpiration
U	internal energy [associated with random translational and internal molecular motions and interactions between molecules, i.e. U = f (local temperature, density)]
v	velocity ($\vec{v}$ = velocity vector; $\vec{v} = v_x + v_y + v_z$)
Veg.	vegetation
W	width (stream channel system); relative wetness of clothing or skin (man system); relative wetness (park, building and street system) absorption
$\delta_{i,j}$	KRONECKER Delta
∇	del-operator, $\nabla = \frac{\partial}{\partial x}\vec{i} + \frac{\partial}{\partial y}\vec{j} + \frac{\partial}{\partial z}\vec{k}$ ($\vec{i}$, $\vec{j}$, $\vec{k}$ = unit vectors in the direction of the x, y, z axes — x, y, z are often the eastward, northward, and upward components of $\vec{v}$)
∇^2	LAPLACIAN operator
μ	dynamic viscosity
ρ	density of matter in question
ρ_i	mass concentration of species $\underline{i}$

Σ	radiative scattering (atmosphere system); summation
$\vec{\tau}$	viscous stress tensor (the elements of $\vec{\tau}$ are τ_{xy}, τ_{xx}, τ_{xz}, τ_{yy}, τ_{yx}, τ_{yz}, τ_{zz}, τ_{zx}, τ_{zy}— see Fig. 3c)
τ	shearing stress or internal viscous dissipation
Φ	potential energy, $D\Phi/Dt = -\rho(\vec{V}\cdot\vec{g})$
Φ_V	viscous dissipation function
ϕ	latitude
$\vec{\Omega}$	angular velocity vector
ℓ	mean free path travelled by molecules between collisions