Chapter 2
Models between Academia and Applications

by Hans von Storch

Abstract

In environmental sciences, models are an indispensable tool. However, the seemingly simple technical term "model" covers a wide range of different conceptualisations and images of the real world, ranging from drastic reductions and simplifications to maximum complexity. These different types of models serve different purposes. The reduced, or *cognitive* models constitute "knowledge" while failing to provide detailed descriptions. The other extreme, *quasi-realistic* models create the possibility of simulation and experimentation of real world systems but fail to produce insight into the system's functioning. While fundamental research commonly tends more to cognitive models and applied research to quasi-realistic models, a comprehensive strategy employs both types of models in an interative, synergistic manner.

2.1 Introduction

To start our discourse about models in environmental sciences, we present three cases.

- a laboratory model of sediment resuspension and erosion (Section 2.1.1.)
- a hydraulic model of tides in a semi-closed basin (Section 2.1.2)
- a numerical model of tides in a semi-closed basin (Section 2.1.3)

In the two first cases, the "model" is a mechanical analog of a real situation, whereas the third case is a prototypical purely mathematical "model." After having discussed these examples, we will address some specific aspects of environmental modeling, which makes environmental science different from classical natural sciences (Section 2.1.4). In Section 2.2 general aspects of models are discussed, and the different purposes of *quasi-realistic* and *cognitive* models are considered in Section 2.3. Concluding remarks are given in Section 2.4.

2.1.1 Laboratory Model

The first case considers the morphology of the sea bed and, specifically, its stability in the presence of bottom shear stress generated by waves and/or currents. In most cases this shear stress is generated by turbulent water motion. When there is no turbulence, the surface will remain at rest, whereas heavy turbulence will cause sediment particles to become eroded and resuspended. The details will depend on specifics of the sediment, i.e., like colonisation by diatoms or benthic animals.

For describing the dependency between turbulence and sediment erosion, a simple laboratory set-up has been designed (Schünemann and Kühl 1993; see graphical sketch in Fig. 2.1). A sample of sediment typical for the area of interest is derived and placed in the bottom of a transparent tube; the tube is filled up with water, and a propeller is placed over the sediment sample. The rotation velocity can be set externally; it determines the degree of turbulence. For a better display, the scene is illuminated by a light placed behind the tube. For three rotation frequencies, the effect on erosion and resuspension is shown in Fig. 2.1. For frequencies below a threshold (middle panel in Fig. 2.1), the water column is transparent; after having passed a threshold single particles float in the water (top right panel); and at the highest employed frequency the lower part of the water column has become opaque (bottom right panel). At this time, not only the top layer of the sediment has gone into resuspension, but also the deeper, consolidated sediment is beginning to become mobilised. When the propeller is turned off, the suspended particles slowly deposit again.

This model does not *explain* why the threshold is as it emerges, or how deep the eroded layer is. It "only" informs us about the existence of a threshold and it allows us to determine these critical numbers. To constitute "understanding," we need to abstract from the concrete set-up, and design a conceptual model, a "Gedankenmodell" (mental model). The laboratory model then serves two functions; first to validate the conceptual model, and, second to specify a series of unknown *parameters*. The *conceptual model*[1] pictures turbulence as the key process; the stress associated with the turbulence causes the adhesion at the surface, reinforced by the presence of diatoms, to collapse. When the top layer has disappeared and the turbulence is strong enough then even the consolidated sediment is disintegrated.

2.1.2 Miniaturisation

The second example features a "model" somehow similar to a "toy model" - namely a miniaturised composition which replicates some features of the original. In the case of a child's toy train, the model moves on tracks and wagons are coupled together and drawn by a locomotive and the like. Other real world features

[1] Note that there may be several, different, or even conflicting, conceptual models consistent with the laboratory model. In the specific case, one could argue that it is not the turbulence but a vertical drag exerted by the propeller. This hypothesis would be consistent with the specific experiment but is falsified after a closer inspection.

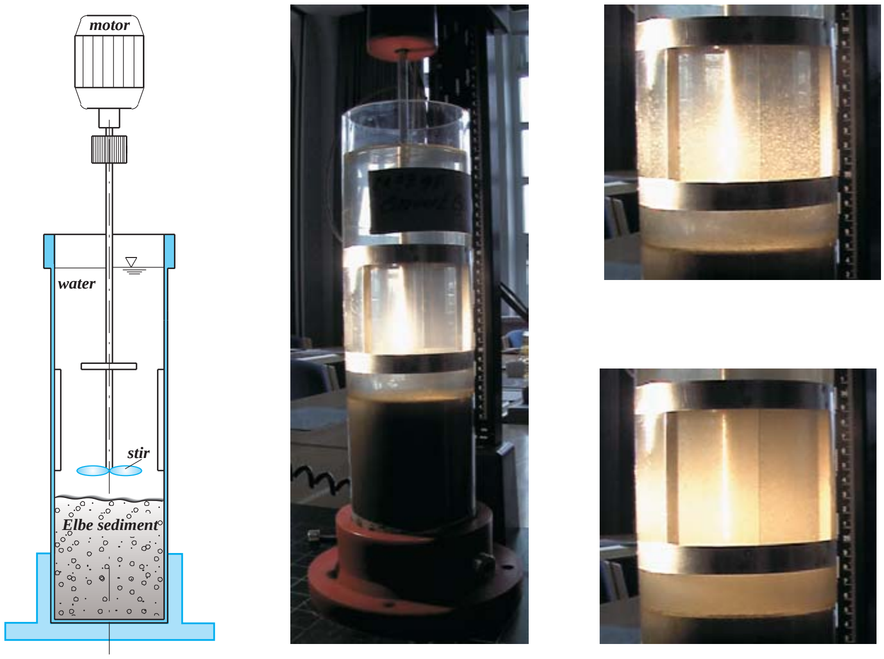

Fig. 2.1. Erosion Stress Laboratory Model. On the left is a sketch of the apparatus, with the sediment in the lower part and 30 cm water on top of it. The propeller generating the turbulence is placed 5 cm above the sediment. In the middle, a photo of the apparatus is displayed, with a very low rotation of the propeller resulting in negligible erosion. In right panels only the water column right above the sediment is shown. In the top panel erosion is about to begin, whereas in the bottom panel the turbulence is so strong so that heavy erosion has been induced.

are not available in the model; for example, in the instance of the toy train, the engine is not really driven by steam but by electricity. Other miniaturised models refer to down-scaled complexes of buildings. In engineering sciences, such miniaturised models have been used extensively in the past. For instance, hydraulic engineering employed huge miniaturisations to replicate the interplay of currents, waves or tides with man-made modifications of rivers or the coast.

Figure 2.2 is a photograph of a downsized model of the Jade Bay in Northern Germany (Sündermann and Vollmers 1972). Is has been scaled to correspond to a real bay with a diameter of about 10 km and with a channel open to the North Sea about 4 km wide. At the open boundary (at the front of the photograph), a sinusoidal tide is imposed. In the basin, currents are displayed by floating white bodies, whose movements appear as white lines on a photograph taken with sufficiently long exposure time. One of such snapshots is displayed in Fig. 2.3; the situation refers to a declining tide with out-flowing waters. The emerging counter- clockwise eddy is marked by two white arrows.

The hydraulic model may be used to provide estimates of the current patterns (Fig. 2.3) as well as of the current speeds during a tidal cycle (Fig. 2.4). The current pattern is symmetric with two eddies in the bay, just before the flow narrows

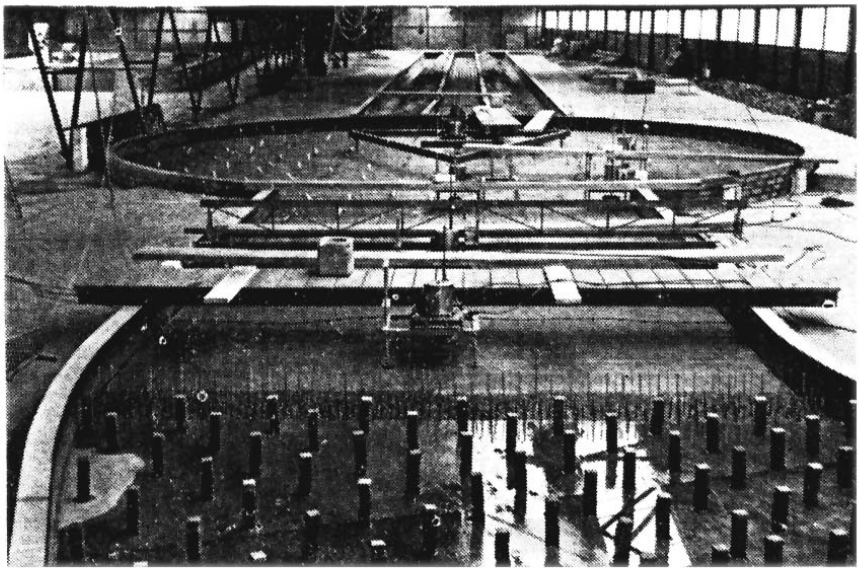

Fig. 2.2. A hydraulic model of the Jade Bay. From Sündermann and Vollmers (1972)

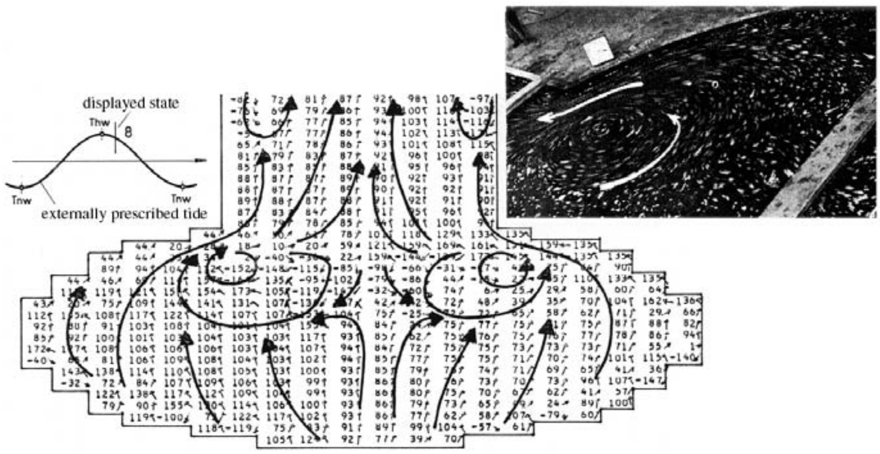

Fig. 2.3. Tidal currents in the hydraulic model (photograph; Section 1-2) and in the numerical model (graph; Section 1-3). The timing is given by the little inset: the tide has just passed the peak level and the water begins to outflow from the basin. From Sündermann and Vollmers (1972)

before entering the channel to the open sea. The speed displays a bi-modal cycle, which is almost symmetric for the inflow- and outflow phases, with maximum speeds of about 70 cm/s.

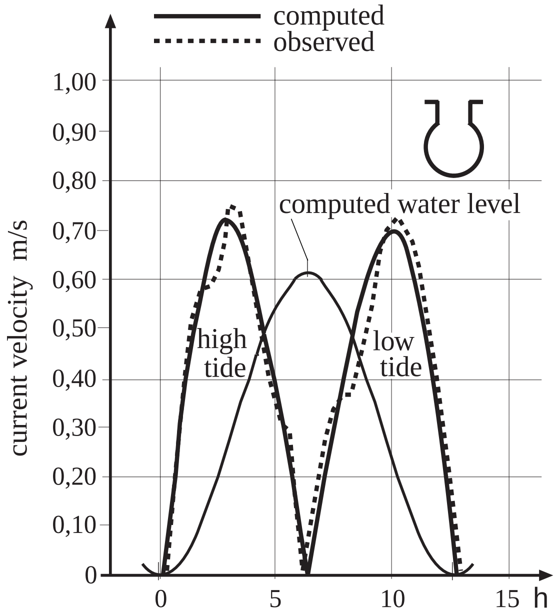

Fig. 2.4. Current speeds and water levels during a tidal cycle in the simulated Jade Bay. The dashed line refers to currents derived form the laboratory experiment (Section 2.1.2), and the solid lines to currents and water levels calculated in the numerical model (Section 2.1.3). From Sündermann and Vollmers (1972)

As in the previous case, the simulation with the hydraulic model does not offer any immediate insight into the *dynamics* of the geophysical system of Jade Bay. It does not tell us *why* there are two opposite eddies. Understanding requires the utilisation of concepts; in this case the principle of conservation of angular momentum. Other questions which remain unanswered are the sensitivity to the depth or the size of the bay. However, the simulation is valuable for the coastal engineer to assess where currents of various magnitudes will appear. Combined with the erosion laboratory model presented in Section 2.1.1, the tidal dependency of suspended matter concentration may, at least in principle be estimated. The value, and purpose of the hydraulic model is to provide a quasi-realistic composition within which certain experiments on the system's sensitivity may be conducted. These simulations provide data which may be used to develop conceptual models and theories about the functioning of the system.

2.1.3 Numerical Models

The same problem of tidal currents in a semi-closed bight, as dealt with in the hydraulic model in the previous Section 2.1.2, has also been dealt with a numerical model. A "numerical" model is a computer code, based on certain mathematical equations (or expressions) after some manipulations such as discretisations or simplifications.

In the present case, the *state variables* are the vertically averaged components of the currents labeled u and v, and the water level ξ relative to the undisturbed level h. For each of the state variables, a differential equation for the change in time is available from dynamical reasoning:

$$\frac{du}{dt} = \sum_i P_i^u \text{ and } \frac{dv}{dt} = \sum_i P_i^v \tag{2.1}$$

$$\frac{d\xi}{dt} = \sum_i P_i^\xi \tag{2.2}$$

where P_i^u and P_i^v are processes acting upon the currents. Equations (1) are in principle given by the Navier-Stokes Equation, whereas (2) is the principle of mass conservation.

The equations have to be solved on a certain area with boundary conditions, such as the tidal condition $\xi(x=0,t) = sin(2\pi\ t/T)$ at the open boundary and no currents perpendicular to the shore line. In the present application the period is $T = 12.5$ hours.

The next task to be solved is the specification of the processes. The formulation of the net divergence is simply $P_1^\xi = \partial(h+\xi)u/\partial z + \partial(h+\xi)u/\partial y$. The scale analysis of the equations of motion (Pedlosky, 1987) informs that the most important "zero order" processes are the pressure gradient force $P_1^u = g\partial\xi/\partial z$ and $P_2^v = g\partial\xi/\partial y$ and the Coriolis force $P_2^u = -fv$ and $P_2^v = fu$ with the Coriolis parameter f. Another important process is the bottom friction in a turbulent boundary layer. The effect of this process on the state variables "vertically averaged current" can not be described explicitly; instead the effect has to be "parameterised". That means, the average net effect on the current is specified, conditional upon the state of the system in terms of u, v and ξ. A parameterisation is an educated guess, and it is usually adopted after its impact on the overall simulation has emerged as an improvement (for a more detailed discussion refer von Storch, 1999, see also Section 11.3.1). Thus, there may be several rather different formulations for the same process. For bottom friction in shallow waters, the following formulation is often adopted:

$$P_3^u = \frac{ru}{h+\xi}\sqrt{u^2+v^2} \text{ and } P_3^v = \frac{rv}{h+\xi}\sqrt{u^2+v^2} \tag{2.3}$$

with a constant friction parameter r. Another process is that of horizontal diffusion, which is often parameterised as

$$P_4^u = A_H \Delta u \text{ and } P_4^v = A_H \Delta v \tag{2.4}$$

with a diffusion parameter A_H and the Laplace operator Δ.

With these specifications, the system is closed; all other processes, be it the effect of variable wind, effects of vertical stratification, the mixing due to shipping, the effect of suspended matter, or the propagation of sound waves in the water are disregarded and considered irrelevant for the problem of tidal currents and water levels. Because of the disregard to all these processes, the model given by equations (2.1-2.4) represents a severely simplified and idealised description of the real world. Using the terminology introduced later in this discourse, the model is an example of a quasi-realistic model, as it has been set up for approximating real tidal currents in spatial and temporal detail. We call it a “mathematical” model.

Before the mathematical model can be implemented on a computer, it has to be discretised. It is transformed from being a infinite dimensional system to a finite system. This is achieved by either replacing the derivatives with finite differences, such as $d\xi / dt \approx \xi(t+\partial) - \xi(t-\partial)/2\delta$, or by expanding the stated variables into a truncated series of orthogonal functions such as the trigonometrics[2] - then the spatial coordinate x is replaced by an index k enumerating the orthogonal functions. Another option is the use of finite elements. In case of the numerical model of Jade Bay, a finite differencing has been adopted. Note that this manipulation further simplifies the model, which we name a “numerical” model.

For what purpose can we use the numerical model? Possible applications are

- attempts to replicate the outcome of the hydraulic model. If both models return similar assessments, they may serve as arguments for the validity of both; if they return conflicting assessments, further analysis is required to decide if one or perhaps both models are “wrong” - in the sense that one or both contradict observational evidence.
- the performance of sensitivity experiments - as for instance: what is the importance of the Coriolis force on the simulated flow regime in Jade Bay? The relative importance of processes, on the formulation of parameterisations and of boundary conditions can be tested.

Both applications have been run with the numerical model of Jade Bay (Sündermann and Vollmers 1972).

In an attempt to validate the hydraulic model, the numerical model was run without invoking the Coriolis force (which could not be considered in the hydraulic model without placing the apparatus on a rotating disk). In Fig. 2.4 the simulated current speed distribution shortly after high tide is shown on the matrix of grid-points; the arrows indicating the directions of the flow are added by hand. The photograph of the laboratory flow with the white lines is consistent with the numerical model. Also the current speeds displayed in Fig. 2.4 are very similar in the numerical and hydraulic model. Based on this evidence, Sündermann and Vollmers concluded that the two approaches return consistent results.

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[2] If $\xi(x,t) \approx \sum_{k=1}^{K} a_k(t) e^{ikx}$ is the truncated expansion, then the spatial derivative is approximated by $\frac{d\xi}{dx} \approx \sum_{k=1}^{K} ika_k(t) e^{ikx}$.

To test the sensitivity of the system to the presence of the Coriolis force, this process was turned on in a second simulation. The resulting current pattern is displayed in Fig. 2.5. Obviously, the current system deviates significantly from the one shown in Fig. 2.3 without the Coriolis force. The currents are no longer symmetric; instead in the left two thirds of the channel the flow is outward, but in one third it is inward. Also, the clockwise eddy on the left has been diminished. Thus, the Coriolis force is found to be a process which should be taken care of; indeed the results obtained with the hydraulic model should be considered with reservations.

The advantage of numerical models over mechanical models is twofold. First, these models are economically much more efficient; the cost of setting up a tank as shown in Fig. 2.2 is by magnitudes larger than setting up a numerical model on a computer. The other advantage is the simplicity to do "observations" in a numerical model; it amounts to adding simple write-commands in the code. These "observations" are accurate, and can be done in high temporal and spatial resolution. Because of this possibility, it was possible to add in Fig. 2.4 water levels simulated in the numerical model, which were "unobservable" in the hydraulic model. However, the ability to get these numbers easily does not mean that the numbers are "right" or meaningful. Instead the numbers *can* be mostly unrelated to the real process, which is supposedly modeled; and *may* reflect to some extent artifacts of the model design. In the present case; however, this seems not to be a problem.

Because of these two advantages, we will consider only mathematical models and their numerical realisations in the following.

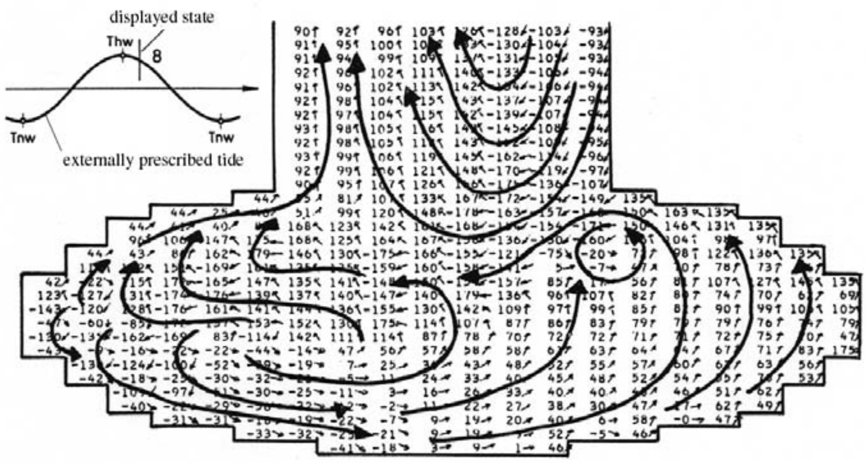

Fig. 2.5. Tidal currents in the numerical model. The timing is given by the little inset: the tide has just passed the peak level and the water begins to outflow from the basin. To be compared with Fig. 2.3. From Sündermann and Vollmers (1972)

2.1.4 Specifics of Environmental Research

Physicists, chemists etc. consider the understanding and prediction of environmental systems just as another physical, chemical etc. problem. Also, everybody

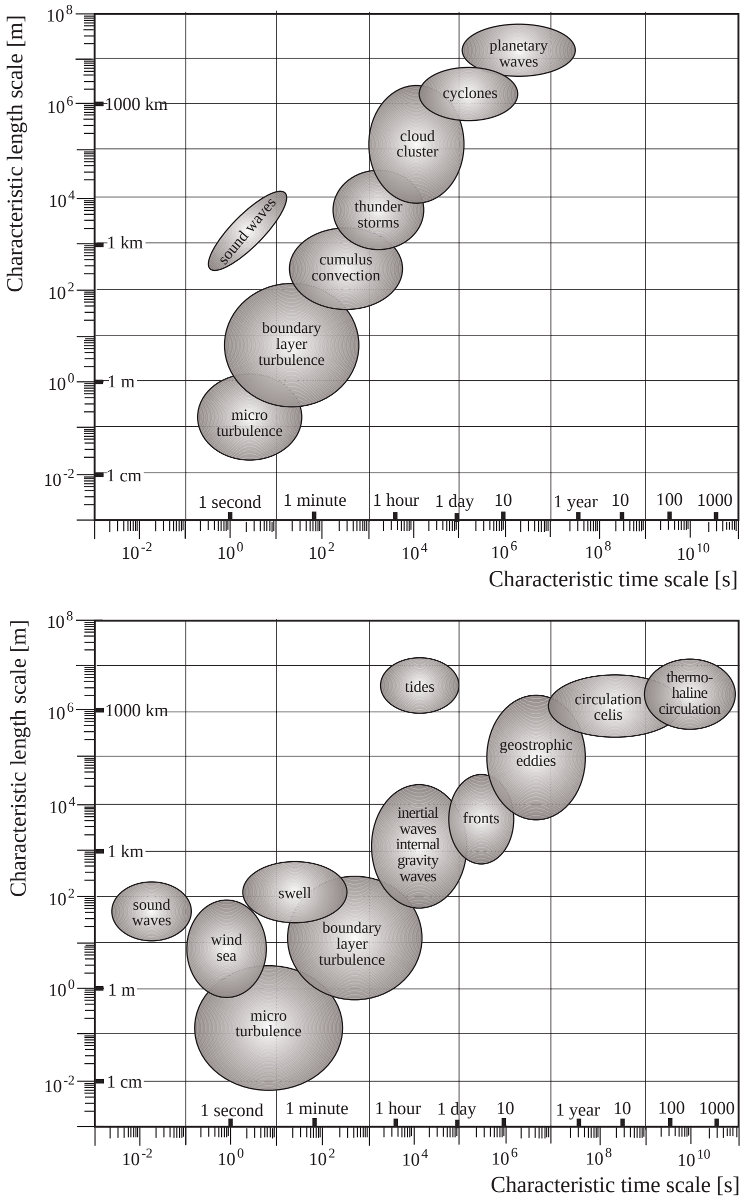

Fig. 2.6. Spatial and temporal scales of atmospheric and oceanic dynamics. From von Storch and Zwiers (1999)

has an intuitive understanding of "the" environment. However, the understanding of the dynamics of environmental systems such as the atmosphere, the ocean, a catchment, or the biosphere; and their interaction requires an approach different than that of a non-scientific lay person or that of the "pure" sciences of physics and chemistry. The scientific employment of the environment poses a number of specific problems (cf. Navarra 1995).

This key difference is the open character of all environmental systems (Oreskes et al. 1994). A myriad of processes interacts in such systems, and they are exposed to an infinite number of external influences. One could argue that the same situation would prevail in a gas, with enormous numbers of molecules interacting with each other and responding to radiations. However, in the environment, the temporal and spatial scales of the processes vary widely, from e.g., the Hadley Cell in the tropical atmosphere to turbulent eddies in the wake of a plane. Moreover, the dynamics at different scales vary in character, and can not be described by some (simple or even complex) similarity laws. Also the external forces are too variable to allow for a complete specification; they range for instance from tidal forcing by the moon, the mixing of waters by a ship and the breathing of people or the effect of diatoms on stabilising the Wadden Sea bottom against erosion stress. This wide range of spatial and temporal scales is displayed in Fig. 2.6 for oceanic and atmospheric dynamics.

There are a number of implications. One is the impossibility to conduct laboratory experiments on the functioning of the *systems* as a whole. Here, following Encyclopedia Brittanica, we understand an experiment as a "an operation carried out under controlled conditions in order to discover an unknown effect or law, to test or establish a hypothesis, or to illustrate a known law." Of course, experiments may be done with sensors on reduced systems[3], but not on the full system. Also, real world *repetitions* are unavailable, which may help to rigorously sort out whether certain phenomena have emerged merely by chance or as a result of certain processes. There is only a limited segment of a trajectory in the phase space; even if the system is ergodic, there are doubts that the phase space is sampled sufficiently well by our limited segment to allow us finding real "analogs."

Second is the presence of internal noise, which is self-organising in the sense that variability appears on all spatial and temporal scales (cf. von Storch and Hasselmann 1996). In principle, the system is deterministic, but the presence of many chaotic processes creates a pattern of variability, which can not be distinguished from random variations.[4] Because of these specific features, two fundamentally different types of mathematical models are used in environmental research:

- One sort is "quasi-realistic" and is supposed to be a substitute reality, within which otherwise impossible experiments can be conducted. A representative of this type is Sündermann's and Vollmers' case discussed above in Section 2.1.4. Such models are also used to extra- and interpolate in a dynamically consistent manner the sparse observations, so that spatially and temporally high resolution

[3] As with the stability of the sediment discussed in Section 2.1.1.

[4] In the case of the tides in Jade Bay, this aspect was not relevant; as only a periodic, purely deterministic forcing was applied, and the considered system is not chaotic but strongly dissipative because of the bottom friction and horizontal diffusion.

analyses of the system's state are constructed (in particular weather analyses, e.g. Kalnay et al. 1996).

- The other type of model, named here "cognitive", is highly simplified and idealised. Because of its reduced complexity, such a model constitutes "knowledge". The geostrophic model $P_1^u = -P_2^u$ and $P_1^v = -P_2^v$ is an example of this type of model.[5] Other examples are Lorenz' chaotic system (Lorenz 1963) or Hasselmann's stochastic climate model (Hasselmann 1976).

In the following we will discuss these two types of mathematical models in some more detail.

2.2 General Properties of Models

Models are supposed to reflect reality. As such they deviate from reality, as the introductory examples have demonstrated.

Models are *smaller, simpler* and closed in contrast to reality, which is always *open*. This difference is attempted to be sketched in Fig. 2.7 and 2.8.

- "Smaller" means that only a limited number of the infinite number of real processes can be accounted for. In the case of the tidal model, processes related to varying density were disregarded; also topographic details on spatial scales smaller than the grid cells' size could not be described. In fact, only the processes P_1 - P_4 were considered.

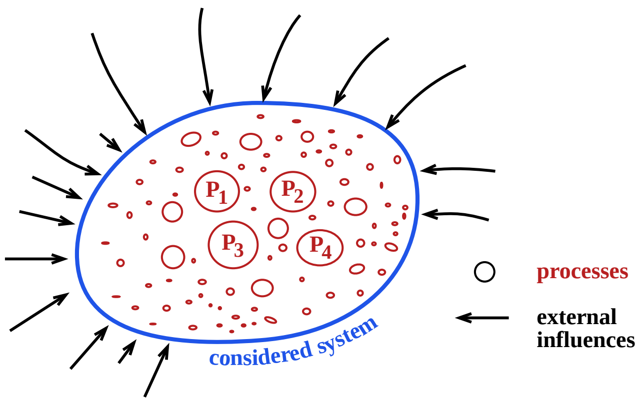

Fig. 2.7. Sketch of a real system, in which an infinite number of processes P_i (open circles) is present, and upon which an infinite number of external forces (arrows) act

[5] For the notation, see Section 2.1.3.

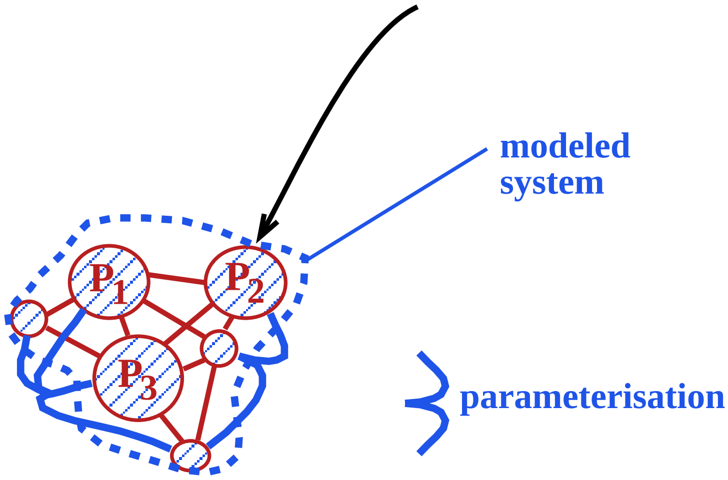

Fig. 2.8. Sketch of a modeled system, in which only a limited number of processes (open circles) and their interactions are represented, and in which the number of external forces is also limited (arrow). Parameterisations are indicated by solid lines crossing the dashed-line border of the model

- In the case of an atmospheric model or an oceanic model, the unavoidable discretisation means that from the overall ranges of scales, as displayed in Fig. 2.6 only a limited interval can be accounted for. A global model describes planetary waves and cyclones, but no boundary layer turbulence in any detail. Similarly, an ocean model resolving internal gravity waves will hardly describe the dynamics of thermohaline circulation.
- “Simpler” means that the description of the considered processes is simplified. For instance, in the case of the Jade Bay current, the horizontal flow is not allowed to exhibit any vertical shear. Furthermore, some of the links to the processes not described by the model are indirectly accounted for by means of parameterisations. Bottom friction is in fact maintained by a cascade of small scaled turbulent eddies, none of which can be resolved by the numerical model. Instead the overall effect is summarily described by the crude parameterisation (2.3).
- “Closed” means that models are integrated with a limited number of completely specified external forcing functions.[6] In case of the tidal model, it was the tidally driven water level at the open boundary, whereas other factors like wind forcing were neglected. As elaborated by Oreskes et al. this is an important philosophical limitation of environmental models, as it implies that the “right” answer of a model may be due to either the “correctness” of the model or an coincidental balance of an incorrect model response and the effect of an unaccounted external influence.

[6] An exception represent models in which randomised external influence factors are specified. An example is provided by Mikolajewicz and Maier-Reimer (1990)

Because of these properties of models, they suffer from a number of limitations:

- A model desribes only part of reality. For instance, the numerical tide model described above is limited to time scales of a tide, to an area small enough to allow for the assumption of a constant Coriolis coefficient and to water bodies of a minimum depth. In its present form it can not be used for predicting water level variations due to meteorological variations or due to runoff from rivers.
- This limitation is sketched in Fig. 2.9 in a space-time-parameter phase space. When setting up a model, the researcher almost always makes assumptions about the time and space scales, and about the range of parameters. In the best case, these assumptions are made explicit, but often they are implicit and unaware to users of models and model outputs.
- Indeed, the choice of the "admissible domain" is a subjective process; ideally it is guided by a rigorous analysis of the relative importance of different processes on different scales. A classical approach to this end is to transform the equations first into a dimensionless form, featuring time and space scales as well as characteristic parameters explicitly. Then, a Taylor expansion allows to discriminate the various terms according to their relative importance (cf., Pedlosky 1987).
- The models can not be verified in the sense that we can with certainty conclude that the model is producing "right" numbers because of the "right" reasons (dynamics).[7] We can compare the numbers with observed numbers and conclude that they are consistent with the observations[8]; we may add to the credibility of the model by analysing the dynamical system and assuring that all first order processes are adequately accounted for. In that case we call the model *validated*. In that sense we may trust the model's output as long as we are applying it within the "admissible" domain depicted in Fig. 2.9. We may be confident that the model may be used for some extrapolations (in Fig. 2.9, an application to the point A would amount to an extrapolation), such as the effect of dredging the inflow channel, but we can not derive knowledge about the system's response to, e.g., making the inflow channel very shallow.
- The problem of making statements *outside* the admissible domain is frequently met in applications. The various claims about anthropogenic changes of climate are based on such extrapolations of models. For instance, if a model is realistic in reproducing the present climate, it is not assured that its response to changing greenhouse gas concentrations is described realistically.

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[7] We will not discuss the meaning of "right" in this context.

[8] "Comparing with observations" is a trivial act if it is reduced to compare an observed map or curve with a simulated map or curve. In general, however, this naive approach is insufficient. When the forecasting capability is indicative of a model's skill, then ensembles of forecast should be formed and overall measures of success be calculated (e.g. Livezey 1995); when the system is unpredictable, then a statistical comparison of simulated and observed data is required; for instance in terms of means, characteristic patterns and spectra (von Storch and Zwiers 1999).

2.3 Purpose of Models

2.3.1 Quasi-realistic Models Surrogate Reality

The main purpose of a quasi-realistic model is to provide scientists with an experimental tool. As such, it is as complex as possible. A quasi-realistic model generates numbers as detailed as the real world (within the limits of spatial and temporal resolution). These numbers are consistent with observed numbers, i.e., to some approximation they are (statistically) indistinguishable from observed numbers. Prototypes are modern climate models, featuring detailed dynamical models of the atmospheric, oceanic and (part of) the cryospheric dynamics. But even if highly complex, it is limited to its specific "admissible" domain in terms of scales and parameters (Fig. 2.9).

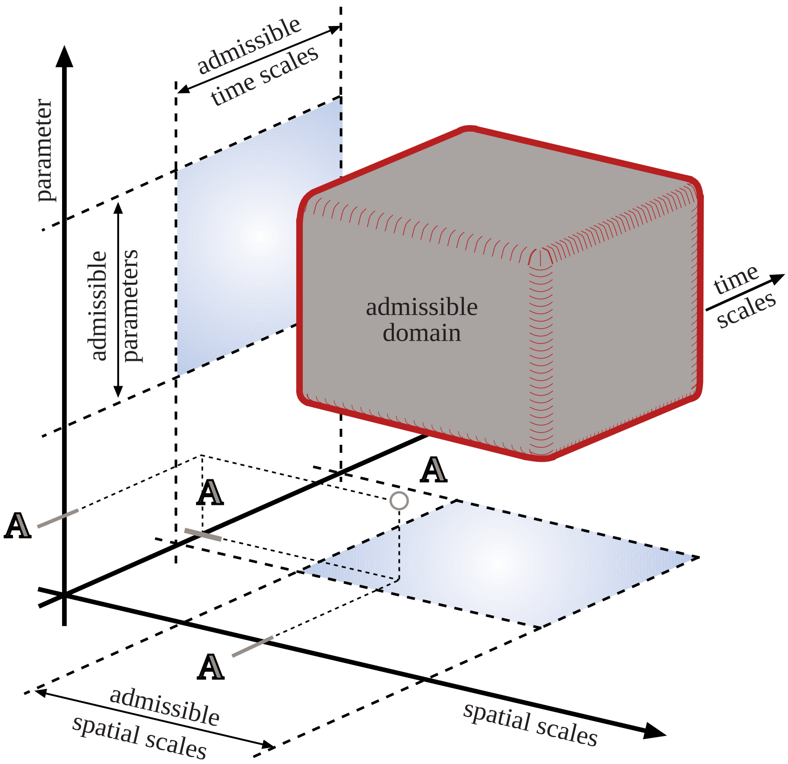

Fig. 2.9. Admissible domain of applicability of a model. Application to point A would be an extrapolation.

Quasi-realistic models are almost always expressed in numerical terms, and rarely as mechanical or other analogs. Essentially, they represent an engineering approach.

A quasi-realistic model is composed of many sub-models, describing the various processes involved in the dynamics of the considered system. These sub-models, or process-models are ideally quasi-realistic models. In many cases, however, the sub-models are strongly reduced to simple approximations and parameterisations.

Quasi-realistic models are used for various purposes:

- They are used to test hypotheses, for instance to determine which of two concurrent processes is more relevant in certain situations, and to quantify the sensitivity of the system to parameters, like the water depth in the case of the tidal basin or the greenhouse gas concentration in the climate change problem.
- Another application is simulation. This accounts for the derivation of scenarios, i.e., of possible future developments given certain changes in the system's ambient conditions. Such scenarios play a crucial role in many managerial decision-making processes, ranging from coastal engineering to climate policy.
- A somewhat different application is the performance of "control runs", i.e. of running the model with real or statistically modeled boundary conditions with the purpose of generating long time series of complete and dynamically consistent data. In particular, climate models are used in this manner, since detailed observations of the deep ocean or the free atmosphere are scarce or only have been available for a few decades. Then, the output of such control runs serves as substitute observations and is used to derive hypotheses about the real world's functioning. In certain applications, such data are also used in managerial decisions, as for instance concerning risk assessment in safety design for off-shore constructions.
- Forecasting of the near-future development of the system is also done with such models. Numerical Weather Prediction models belong into this category.
- A relatively modern application concerns the analysis of environmental states. Because of many degrees of freedom and practical barriers rendering certain variables unobservable, a complete analysis of the state's system is all but impossible. However, an intelligent use of dynamical knowledge encoded in quasi-realistic models allows for the dynamically consistent interpretation of sparse, and to some extent uncertain, observations (Robinson et al. 1998). Such tools are called *data assimilations*, and their output "analyses". Note that analyses are merely best guesses of the real situation; it is a skillful approximation of the real situation; sometimes measures of certainty of the approximations are given.

In this way, consistent and complete data bases of the system are provided.

Quasi-realistic models do not provide immediate knowledge. Being most complex, the numbers need a skillful analytical treatment before conclusions can be drawn. The knowledge is hidden in the numbers; to extract this knowledge the output must be interpreted with the help of cognitive models, i.e., concepts derived from dynamical reasoning, screening observations, previous numerical experimentation, or simulation with statistical techniques (von Storch and Zwiers 1999).

2.3.2 Cognitive Models: Reduction of Complex Systems

Cognitive models are characterised to be of minimum complexity; they describe all processes of "first order," i.e., all processes which are required to describe the main features of interest. The description of these processes is stripped down to the bare essentials. As such, cognitive models constitute knowledge. When using the phrase "we understand a system" (for certain scales and parameter ranges), we actually mean "we have a cognitive model to describe the phenomena we observe (or expect)." As such, the formulation of cognitive models is a key method in fundamental science.

A prototypical case is the zero-dimensional energy-balance model of climate (e.g., Crowley and North 1991), in which the Earth's surface temperature is described as being in balance between incoming short wave radiation and outgoing long-wave radiation, and the two processes modulated by albedo and back scattering. Often, the needed parameters in such models are determined semi-empirically.

Of course, cognitive models may also be built with the intention to derive hypotheses, i.e., by suggesting certain processes to be of first order and to derive hypotheses about implications. Then these hypotheses may be examined with the help of observational evidence or simulations with quasi-realistic models.

In most cases, the derivation of cognitive models is left to the insight and ingenuity of the researcher. A classical case are the two rivaling explanations of the Gulf Stream put forward by Munk and Stommel in the late 1940s (see Pedlosky 1987). However, there are ways of pursuing the goal of a "good" cognitive model in an objective manner. The scale analysis mentioned above, based on a Taylor expansion of the relevant parameters in the dimensionless equations is one such way. Another general one is Hasselmann's *Principal Interaction Pattern* concept (Section 11.4: Hasselmann 1988; von Storch and Zwiers 1999).

2.4 Conclusions

In this discourse we have discussed the scientific approach of "modeling," which is usually not conceptualised. In about all scientific disciplines, classical natural sciences, environmental sciences, social and cultural sciences, the term "model" is used. A joint property of all these models is that they refer to a complex part of reality and that they are simpler than reality. Otherwise, these models vary widely in concept, design and purpose. Nevertheless everybody seems to believe that his or her use of the term is the genuine one, supposedly understood by everybody else. Examples are mental maps in social sciences, digital elevation maps in earth science and world models in economy. Some models are static, like a map, others are dynamic, including a predictive capability. Some models are scientific constructs, others are social or historical constructs.

In interdisciplinary cooperation, then, severe misunderstandings emerge and hinder the flow of ideas and knowledge between the different traditional branches of science. This is in particular a problem in modern environmental sciences, which are rapidly expanding across traditional disciplinary borders.

In this paper we have attempted to characterise two major types of models employed in physical environmental sciences; cognitive and quasi-realistic models. Both play a key role in the progress of environmental science. Indeed, in this science the classical loop "… □ *experiment* □ *theory* □ *experiment* □ *theory* □…" is replaced by the loop "… □ *quasi-realistic* □ *cognitive* □ *quasi-realistic* □…".

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