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Earth Systems Science Course in Watersheds & Coastal Zone Simulation Modeling
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"Earth Systems Science Approach"

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EARTH SYSTEMS SCIENCE APPROACH

1. PROBLEM (System Dysfunction)
   Land-use practices and discharges in the watershed are impacting the resource capital of the Coastal Zone.

2. OBJECTIVE (Scientific Simulations)
   Scientifically defendable linkages between Forcing and Response that can assist policy decision making.

3. DEFINITION (Boundaries of System)
   Keep primary functionality within system to minimize coupling with adjacent systems and to include sufficient response ↦
   - System: Watershed - River - Estuary/Delta/Coastal Zone
   - Open Boundary: Coastal Ocean
   - Vertical Boundary: Atmosphere, Sediments
   - Internal Sources: Emissions, Discharges

4. FORMULATION (Optimize Information & Minimize Structure)
   - Input Parameters
   - Response Indicators
   - Primary Processes
   - System Information Parameters
   - Process-Critical Parameters

5. INFORMATION BASE (Input & Validation Data, Monitoring)
   - Input data
   - Validation data
   - Calibration/Hindcast
   - Monitoring

6. SOLUTION (Models)
   - Conceptual Models
   - Definition of Subsystems
   - Quantification of Processes
   - Coupling of Processes & Subsystems
   - Validation and Calibration

7. IMPLEMENTATION (Generation of Output)
   - Sensitivity & Simulation
   - Design Iteration
   - Translation to Policy Language

THE SYSTEMS APPROACH TO EARTH-SYSTEMS SIMULATIONS

I IDENTIFY A PROBLEM -

This is usually some Dysfunction, Impact or Change within some system that is causing economic, social, resource problems. These should guide our construction of a simulation model. Examples could be:

- more pollution in the ground water
- the fish yield is declining
- too frequent flooding
- city is paying too much for water treatment
- requirement for buffer zones is questioned

These usually concern some decrease in the 'free services' of Natural Capital. The reason for quantification and simulation would either for management or science or both.

II IDENTIFY THE SYSTEM

Define the system such that the primary functionality is within its boundaries.
That is, we must define the system (subsystem) to contain the functionality causing the Problem in order to simulate the cause-and-effect relationship. Often one must ask: What sphere of functionality needs to be considered? Several guidelines should be followed:

1. Avoid strong feedback loops from within your defined system to any forcing outside the system. This is equivalent to requiring the boundaries to be set at points of weak coupling. The criteria can be Functional, Spatial or Temporal; for example in selecting subsystems of an automobile system:
    - Functional - electrical, braking, mechanical, etc.
    - Spatial - front versus rear.
    - Temporal - maintenance monthly, after 3,000 km, etc.

2. If some external dynamics drive a source, then specify it as an external source; for example:
    - Agricultural chemicals are imported from another area.
    - Estuary outflow imports salt water.
    - Fish spawn in the ocean but spend juvenile stage in estuary.

   In each of these cases the dynamics external to the system are assumed to be stable and not affected by what occurs inside the selected system. If this assumption should become invalid, then the boundaries must be extended.

3. Any such an external source must be quantitatively represented by
   - Real-time monitoring.
   - Data simulation.
   - Calculated deterministically/empirically

   In the latter case, calculation should avoid strong dependence on internal variables, which would constitute a feedback loop between inside and outside. For example, if in the above case the spawning in the ocean depended strongly on the survival of the juveniles in the modelled estuary, then the boundaries of the system would have to include the adult fish stock in the ocean.

III PROBLEM REDUCTION

Since we can not hope to model everything within a system, we will want optimize the structure of the simulation model relative to the information needed about our Problem. This means we must:

1. Look for indicator parameters and processes, whose behavior will provide the most information,
2. Make sure that the level of complexity is balanced within this choice of parameters and processes

These above two requirements are facilitated by:

3. Asking First-order Questions about the Impact
   - Is it possibly due to natural variability?
   - How is it forced - by an event or by a trend or both?
   - Is Anthropogenic forcing implied?
   - Could it lead to a change of state?

4. Linking fundamental processes
   - What are the key indicators of the Impact: e.g. locations, concentrations, ratios, species, etc?
   - What internal flux of mass, energy, information are involved producing the Impact?
   - Identify the processes and parameters associated with these fluxes and link tem up working backwards through the system from the Impact (Response) to the Forcing.
   - Identify any important Feedback Loops within this chain of processes

IV CONCEPTUAL MODEL

At the point in which we are specifically designing how we will quantify our model we need to visualize it. This is done by constructing a flow diagram that indicates the external connections or boundary conditions, the major compartments of the system and the internal processes and information that control the flow of mass and energy through the system. It also must represent the output of the model. Thus, there are several reasons for constructing a conceptual model:

- To have a visual summary of the model structure
- To help evaluate if the model is properly balanced
- To serve as a guide to translating it into EXTEND blocks
- To serve as a diagnostic tool.

There are several steps that we can follow in constructing a Conceptual Model:

1. Choose the language,
    - Examples: Odum, Forrester, Extend, etc.
    - Symbols representing storages, processes, inputs, etc.
    - Make all connections.
    - Indicate all Decisions and Feedback Loops

2. Choose systems parameters
    - For each of the systems parameters, connect from forcing to impact through the system.
    - Start simple and refine. Keep level of detail balanced.
    - Make sure that the flow of information is included as appropriate.

3. Represent the Forcing Boundary Conditions and Internal Sources.
    - Check systems boundaries to be sure that there are not important feedback loops linked out of the system.
    - Check that all inputs can be represented.
    - Inventory all significant internal sources.

4. Define Sub-systems (Watershed, River, Estuary, etc.)
    - Make a blow up of each of these sub-systems.
    - Check connections between these sub-systems.

5. Reality Check.
    - Make sure that this conceptualization will deliver information regarding the original Impact Problems.
    - Make sure you can convert Model Output to Social-Economic Indicators relating to the original Impact Problems.
    - If the above two conditions are not met, return to I PROBLEM DEFINITION and reconsider.

A simple example, of an Odum Diagram, is shown in the enclosed Figure.

V INFORMATION BASE

After constructing the conceptual model, it should be clear the type of information/data would be needed to set up the model. These fall into two categories:

1. Formulation of processes, usually taken from literature. If not approximate dependencies can be constructed using Dimensional Analysis (below)
2. Input data, usually taken from various sources or from contemporary field programs.

Again the constraint of retaining a balanced model should be remembered. This implies, for example, that an hourly time series of air temperature is not needed if one has only daily sunlight values. The model would be limited to a daily time step, and consequently daily averages of temperature should be also used. Of course, this limits the model to processes that have response times less than a day, etc.

5. Formulation Table
    - Construct a Table with describing each of the above items.
    - Make a dimensional check of all parameters at every connection.
    - Include relative level of accuracy expected and error conditions.

An example is also given in enclosed Table.

VII COMPUTATION

This step involves running the subsystem models, making sure that they work properly. The subsystem models are then connected up and the complete system model is run and calibrated.

1. Subsystem check out
    - Check dimensions
    - Check connections
    - Run Mass-Balance checks on sub-components
    - Validate sub-components

The Validation process involves making sure the model makes the calculations correctly. To avoid difficult debugging, it is recommended that the model be constructed in a sequence of sub compartments and the output of each should be separately validated (e.g. by hand or with another program, as EXCEL, etc.). Extend has several ways to assist you in debugging:

a) The Show Animation command in the Run Menu allows you to see many of the values as the model progresses.

b) If blocks are incorrectly linked the model stops and alerts the operator.

c) There are several blocks that are specifically helpful in debugging, some are:

- ReadOut Block in Generic Library allows you to determine the value of a parameter as the model runs.
- I/O Plotter in the Plotter Library is always useful to understand the quantitative output. Below the plot there is a table of values for the entire sequence of the run.
- Integrate Block of the Generic Library integrates a parameter over the length of the run.
- Mean&Variance Block of the Generic Library provides statistical information on any parameter.

d) The Debugging Menu (p. 260) describes other ways to trace a problem.

2. Iteration. The modeller might want to make a preliminary control on the subsystem output relative to some known data. This control may involve iteration on the subsystem construction. Here it is important not to make changes randomly. One must first determine if the poor results are due to design, in which case one should return to Problem Reduction step 3 or the Conceptual Model step (4) to rethink the problem, or to poor formulation, in which case one should return to Construction step 6.

3. Make Simulation Runs. The Simulation refers to the use of the model to predict a response for the system, within its Range of Validity. If we have designed the model well, we can provide an indication of error with every simulation run. For example, if the question concerns the response of a system if the pollutant input is doubled (within its Range of Validity) the error might be determined by the calibration data. But if the input is increased by an order of magnitude (beyond the Range of Validity) the estimated error may be excessive. Some points about the data used for simulation runs:

- Input Data: Use concurrent data for external and internal sources.
- Validation Data: Conduct observations at process 'choke points' in the system (points where mass flux is least ambiguous).
- Calibration/Hindcast Data: Run model with a consistent data set from previous observations; if this data is incomplete conduct calibration at choke points where it is complete and/or fill in data set with innocuous data.
- Simulation Data: Use real-time, concurrent data as available plus simulated data to fill any gaps.

4. Output

- Critique Model. Describe model through using above steps as guide. Include errors and ranges of validity. Indicate sensitive connections or processes and explain if this sensitivity is thought to be real or a result of a poor simulation of a process or data.

- Translate model. If the model is used to simulate management questions, the model output must be translated into a result readily understandable by non-scientific. For this reason, the output is often converted to indexes or simplified plots and tables. Any conversion of output that involves a loss of information should be accompanied by an explanation.

SYSTEMS CONCEPTS

Systems Theory

Systems Approach. The systems approach devises strategies to extract information on the functioning of these systems that could not have been garnered from a sequence of subsystem-scale studies. Systems Theory encourages disciplinary integration of science in its broadest definition, particularly in considering strongly-forced, open systems in the sense that the conditions on energy and information are continually changing, making improbable any steady-state solution in favor of a "continuum of reorganization" of the dynamics and structure of the system. Much of the change is stimulated by non-linear internal reactions to trends in external forcing. These changes may arise in mass storage in food web structure, etc. and can be irreversible. This argues for more inclusive models that capture information concerning changes in systems dynamics and their consequences. Assumptions of steady state and linear predictions of systems problems are risky approaches.

Systems Theory

A central theme of General Systems Theory (Bertalanffy, 1988) is that complex, non-linear systems function differently *in vivo* than a separate scrutiny of their component parts might indicate. Several corollaries are that:

Every object or substance represents an interaction within its resident system. That is, every object has a purpose within a system and that purpose is more important than the object itself.

Godel's Theorem

No system understands itself because more of a systems components are needed to analyze and understand than just to function. A car and driver can function very well without either understanding themselves or each other completely. You can't figure yourself out by looking at your navel - i.e. a full description of a component like yourself requires also a description of your interactions with the rest of your community.

Reductionist

Most science in this century could be described as reductionist in the sense that the effort has been to investigate objects and sub-systems into smaller and smaller scales to achieve a better resolution in the understanding of their functionality. While a necessary and essential part of modern sciences evolution, its inadequacy, according to the Systems Theory, in describing large natural systems is not generally recognized. Furthermore, science itself has become more strongly specialized along disciplinary lines and much of the modern technological advances have favored detailed, hi-resolution measurements. Consequently, most field research has been, necessarily, constrained to specialized sub-disciplines and smaller-scaled functional units or geographic locations.

Holistic

Suddenly as the scale of anthropogenic impact becomes more evident and sustainable options for managing natural systems becomes more urgent, science is being asked to understand and help solve problems occurring within these systems. Much of science would ask for more time to complete the reductionist inventory of all processes before switching to a top-down holistic approach. It is sort of like painting a chair while sitting on it. On the other hand, Since, one can not bring a large ecosystem into a laboratory, one must evaluate them with Simulation Models coupled with in-situ observations and process studies.

Earth Systems Science.

Earth Systems.

Earth Systems can be considered as Human Environmental Support Systems. More exactly, they are the collection of large-scaled systems which are coupled directly to Human society through their functioning as support systems (e.g. agriculture) or indirectly through their contribution to the stability of the earth's biosphere (e.g. rainforests, atmosphere, etc.).

Earth Systems Science

The multidisciplinary effort to quantify Earth Systems is referred to as Earth Systems Science. The rationale for its evolution stems from the urgent need to:

- conduct research on Earth Systems, as opposed to fragmented problems within these systems (e.g. local pollution or habitat degradation);
- evaluate the stress imposed by the variability and trends in anthropogenic forcing relative to that of natural forcing;
- construct a feasible quantitative coupling between Economic and Earth-Systems models for evaluating the costs of the goods and services provided by Natural Systems.

All three of these needs are related to the objective of trying to evaluate the impact on Earth Systems in both scientific and economic terms in order that their management and preservation be inserted into the economic equation.

Ecosystems

System

An assemblage of components that interact together in space and time for some functional purpose. System may be nested one within another and/or they may overlap with other systems.

Ecosystems

A functioning biotic community together with its abiotic environment, its interactions with that environment, and the complete set of connections external to it. Examples of levels of organization: in Natural System: organism - population- biome- biosphere; and the parallel in an Industrial System: assembly unit - factory - industry - global economy. All ecosystems have the four main components: Abiotic, Producer, Consumer, and Decomposer.

Dynamic Equilibrium

A system moving/changing under the condition of a balance of forces, and therefore steady over an integrated time short with respect to the systems life time but possibly long with respect to the lifetimes of individual components.

Feedback

A connection (mass, energy, information) between the output and the input of a response function.

Feedback Loop

If a perturbation in the input results in a significant in the output, through a feedback, then a feedback loop is established. If the output is so amplified and continues to grow, then a positive (destabilizing) FBL is created. If the output is reduced and continues to diminish, then a negative (stabilizing) FBL is created. The predominance of negative FBLs is a necessary condition for maintaining dynamic equilibrium (**Cybernetic Control**).

System States

Many systems that grow do so until they reach a state of equilibrium between their E (energy) input and E loss. This growth can occur in stages, or a sequence of metastable states, until the highest (least entropy) state is reached, the climax community. With decreasing entropy comes increasing PE. The general process is called succession, and in reverse it is called degradation.

Open and Closed Systems -

Open - require mass and energy inputs
Closed - requires constant energy input
Isolated - received no mass or energy inputs

Stored Energy

Energy that enters a system and is stored within, that is not passed out of the system as unused or wasted is called Stored Energy. Mechanical potential energy and chemical potential energy are common types of stored energy, as is fat in biological systems.

Tolerance

This term refers to the range of an environmental parameter in which an individual, population, or ecosystem can operate.

Entropy

Entropy is a measure of disorganization. The word negentropy is sometimes used to indicate a measure of organization. Rainforests are natural systems of minimum entropy and maximum negentropy.

Biodiversity

Resilience reflects the ability of a system to withstand disturbances. It is generally analogous to stability. Stability refers to the state, or dynamic equilibrium of the system, whereas resilience refers to a specific type of disturbance, as with resilience to fire. Greater diversity leads to greater resilience.

Diversity describes the number of species inhabiting an area. The distribution of species may vary in type (with a few dominant species) or in space. Numerous factors affect biodiversity as indicated in the following table. One can see immediately how anthropogenic impact is threatening diversity on all accounts.

Factors Increasing Diversity	Factors Decreasing Diversity
• Diverse habitat	• Environmental stress
• Moderate disturbances	• Extreme disturbances
• Favorable to recycling	• Limited resources
• Small variations between disturbances	• Large variations between disturbances
• Middle stages of succession	• Introduction of alien species
• Evolution	• Geographic isolation

Liebig's Law of the Minimum

Every ecosystem (community, organism, dude, etc.) is limited by the essential element in least supply. This law is generally used in reference to matter, as in "phosphate-limited" for phytoplankton or "Chocolate-limited" for Suzy. However, sometimes you will see references to light-limited for plants. Liebig himself formulated this all in 1830 as he lay around and starved to death many innocent plants and ate chocolate with Suzy.

More generally the term **limiting factors** refers to a substance that limits or regulates abundance, productivity, influence, distribution of organisms. They are important in determining niche distribution and diversity.

Irreversible Changes In State

With changes in forcing, ecosystems have the opportunity to recover - absorb the perturbation and continue to increase their state, a state of higher PE, or to decrease their state - a state of lower PE. If a system degrades to a lower state and cannot recover (within many generations) without an extraordinary external energy input, then the degradation is irreversible.

Sustainability

The characteristic of maintaining dynamic equilibrium in a system without net growth in mass and energy inputs. Negentropic growth is permitted through higher quality information input.

In the context of the Environmental Revolution, **Sustainable Development** is used to define a growth " . . . that meets the needs of the present without compromising the ability for future generations to meet their own goals." Brundtland Report '87.

Maximum Power Principle, sometimes referred to as 'The 4th Law of Thermodynamics' or 'The Survival of the Sharers':

Systems prevail that develop designs, which maximize the flow of useful energy, particularly, systems that have ways to store energy in more useful forms (Lotka 1992, Odum 1983). A useful form of energy is one that can readily utilized by the organism. When energy input to an organism is variable, internal storage mechanisms serve to uncouple the functioning of the organism from this input variability. This holds for an ecosystem or an organism. Eating can be fun, but continuously?

The Maximum Power Principle has some extremely important ramifications that are applicable to human societal behavior. This significance is lost due to an overemphasis on another ecological principle: the Survival of the Fittest, which is used to justify competition in our society. Actually, the Maximum Power Principle is the overriding law. While they are both valid, the Maximum Power Principle tends to prevail on a systems level whereas the Survival of the Fittest (SOF) tends to prevail on an individual level. While limited competition can be constructive, competition to the point of monopoly is destructive for a system because it increases entropy. The Maximum Power Principle effectively says that the system (or components of a system) will survive is the one that best utilizes its resources (energy & mass) - because by so doing it will obtain maximum usage, greatest stability and diversity.

Type I and Type II Errors

Type I error occurs when one rejects a true hypothesis.
Type II error occurs when one accepts a false hypothesis.
These are similar, the difference being in the way they are posed (see Schrader-Frechette and McCoy, 1993). The weight of these errors is taken as the risk factor associated with the hypothesis multiplied by the probability its truth (or falseness). The 'risk' is often treated as the monetary 'cost' incurred by an erroneous decision. To evaluate, one would take the probability (0 to 1) of the validity of the hypothesis and multiply by the cost.

Examples: Type I error, considering Global Climate Change to be a wrong hypothesis; Type II error considering the Titanic to be unsinkable.

In the case of a natural system, irreversible loss may not be estimable but it can easily be several orders of magnitude greater than the cost of avoiding the loss. For example, if the cost of a Greenhouse Climate were 1000 times the cost of reducing emissions and if the probability of the Greenhouse hypothesis being true were 60%, then committing Type I error would be 600 times worse than not committing it.

Modelling

Boundary Conditions

Specifications of mass, energy and information exchange as function of time at the spatial boundaries of a system. May be inputs or outputs - but usually the output (response) is solved for and the inputs are prescribed.

Initial Condition

The starting condition of the interior dynamics and boundary conditions at the time a model simulation begins.

Series Connection

Output of one response function becomes input to another response.

Paralleled Connection

Input passes through two response functions simultaneously and their output is summed.

Deterministic

Functionality and variability are expressed mathematically, but derived from analytical expressions based on theory.

Empirical

Functionality and variability are expressed mathematically or in tabular form, but derived from observed data.

Stochastic

Functionality and variability are expressed empirically but based on statistical (probabilistic) relationships.

Resolution

Separation in space and time over which calculations are made.

Coverage

Extent (area, time) for which calculations are made.

Simulation,

Simulation describes an attempt when used as an adjective for Data or Process:

- Simulated Data is that which has been generated by representing its general spectral, statistical, and/or functional characteristics.
- Simulated Process is an approximate analytical, empirical or statistical functionality for a process that is scientifically defendable over a given range of the independent variables.

2. Validate

- Making sure the model, or some sub-component, produces values that are mathematically correct for the given formulation.
- Validation does not necessarily imply accuracy.

3. Calibrate

- Making sure that the model, or some sub-component, produces an output comparable with observations for an input concurrent with those observations (also referred to as Hindcasting).
- The model performance under this test does reflect its accuracy (the ability to produce a reference value for the output under a given set of conditions). Unfortunately, for natural systems there are many 'given set of conditions' for which we would not have observations on their reference output.

4. Sensitivity

- System Sensitivity. Model, sub-system or component sensitivity implies a comparison of the ratio of change in output to change in input. If the model output changes a lot for a small change in input, then it is 'sensitive' to that input. See below.
- Error Sensitivity. Sensitivity is also used to describe the relative degree of error between two methods of formulation or observation. If one has a choice of formulation, one might want to use this test.

Validation

Confirmation process of computations made by a model.

Calibration

- How is a systems model treated to simplify the quantification of a systems' functioning?

Clue: What does an indicator parameter do?

- What is the logic for maintaining the same level of accuracy (detailed of representation) for all major components of a model?
- If an input is not known deterministically how could it be represented in a model?
- What would be the "upper bound" of a tolerance criteria for a Frontier Economy (open system) with respect to the relation with the productivity of its supporting Earth System? Yikees!

ICTP Earth Systems Science Course, 2-13 Oct 00

EARTH SYSTEMS SIMULATION MODELLING

ATMOSPHERIC INPUT

A. The atmosphere provides much of the Mass (H_2O, HNO_3, H_2SO_4), Energy (radiation, wind) and Information (input variability) to terrestrial and aquatic systems.

B. In designing the Coastal Watershed Simulation Model (CoWaSiM), we consider atmosphere as an Input to the system because most of the fluxes are one-way, that is, without feedback or interactive loops. However, if we were considering directly the problem of local air emissions, we might include the local atmosphere as part of the system; for example, in estimating how much local NO_x and NH_4 emissions impact the local terrestrial aquatic system through acid deposition.

C. Important atmospheric inputs and processes for CoWaSiM

1. **Water**
   Function: Water is the primary medium for transporting physical, chemical and biological substances from land to sea.
   Processes: Precipitation is a function of the regional-to-local meteorology: the water-vapor content of the dominant air masses, season and the processes controlling local condensation and evaporation.
   Data: Data for the CoWaSiM are taken at one or more points (about 50-km scale) in the watershed where data from meteorological stations are available.
2. **Air Temp**
   Function: Controls the heat and water-vapor exchange between the atmosphere and vegetation soil and water. The heat exchange varies the ambient temperature and therefore the biotic metabolism of terrestrial and aquatic ecosystems.
   Processes: Also a function of local/regional air mass-structure and dynamics.
   Data: Data from local meteorological stations.
3. **Wind**
   Function: Controls the processes of evaporation (land and sea); affects the transport of particulate material (land); drives much of the circulation and mixing (sea).
   Processes: Also a function of local/regional air mass-structure and dynamics.
   Data: Data from local meteorological stations.

4. **Radiation** (Included as Atm Input, because it passes through and is modified by the atmosphere.)

Function: Solar input causes direct heating, provides radiation for photosynthesis. UV causes certain impacts, i.e. DOC degradation, genetic damage and growth inhibition in excess, and vitamin synthesis in normal amounts. IR radiation balance is important for the surface heat balance.

Processes: Function of season (latitude) and atmospheric filtration by water vapor, green house gases, etc.

Data: Data from local meteorological stations.

5. **Acid Deposition**

Function: provides significant proportion of the nitrogen to most terrestrial and coastal marine systems. Contributes to soil leaching of essential cations, distorts the vegetation nitrogen cycle through direct uptake, and contributes to ground water accumulations.

Processes: A number of processes link the emission of nitrogen or sulfur compounds with its ultimate site of acid deposition.

Advection and Convection: The respective horizontal and vertical transport of substances that control the length and direction of their trajectory (can be 1 to1000 km)

Direct Transport. As a passive aerosol particle or gas.

Indirect Transport: As a reactive particle or gas that is chemically transformed while being transported.

Diffusion: Small scale movements that disperse a substance in 3-D while being transported along its trajectory.

Emission: Contributing to longer trajectories are higher chimneys, warmer emissions, smaller particles and less reactivity; contribution to shorter trajectories are less elevation of emission, more are turbulence, greater wind shear, and more reactivity.

Oxidation: Can occur in either gaseous or aqueous phase. In gaseous mainly by OH^- but also by HO_2 and O_3. SO_2 is slower at ~1%/hr and NO_x at ~10%/hr. In aqueous phase (mostly in clouds) oxidation is about ten times more rapid and is due to H_2O_2 and O_3.

Dry Deposition: Occurs through direct contact with vegetation, soil and water. Depends on the type of surface (active absorption or passive deposition) and on the local convection (greater for subsiding air as in a high pressure condition).

Wet Deposition: Nucleation occurs when water condenses on an aerosol; it is greater for larger particles. Diffusion for smaller particles can occur in which the particle diffuses inside a water droplet (also a function of solubility). Inertial Attachment occurs when falling water droplets collide and absorb particles.

Data: Atmospheric deposition is difficult to measure, particularly dry deposition, and most meteorological stations are not equipped to do so. Bulk values are usually taken from the literature.