African Forest Forum

A platform for stakeholders in African forestry

Climate Modelling and Scenario Development

A COMPENDIUM FOR PROFESSIONAL TRAINING IN AFRICAN FORESTRY

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Front cover photos: *Milicia excelsa* in a sacred forest at Toffo in Southern Benin (left), Zio riverbed at Alokoegbé-kpota in Southern Togo (middle), Private plantation of *Moringa oleifera* in southern Benin (right). Credit: Dèdéou A. Tchokponhoué.

Back cover photo. Dense foliage of Milicia excelsa in a sacred forest at Toffo in Southern Benin. Credit: Dèdéou A. Tchokponhoué.

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Abbreviations and Acronyms

AAU	Assigned Amount Units
AFF	African Forest Forum
AFOLU	Agriculture, Forestry and Other Land Uses
C	Carbon
CCBS	Climate, Community and Biodiversity Standard
CCX	Chicago Climate Exchange
CDM	Clean Development Mechanisms
CERs	Certified Emissions Reductions
CH4	Methane
CO2	Carbon dioxide
DOE	Designated Operating Entity
ERPA	Emission Reduction Purchase Agreement
ERUs	Emission Reduction Units
ETS	Emission Trading System/Scheme
EU ETS	European Union Emission Trading System
FCPF	Forest Carbon Partnership Fund
GHG	Green House Gases
IETA	International Emissions Trading Association
JI	Joint Implementation
KP	Kyoto Protocol
MRV	Measurement, Reporting and Verification
NGO	Non-Governmental Organization
PDD	Project Design Document
PES	Payment for Ecosystem Services
PIN	Project Information Note
PP	Project Participants
REDD+	Reduction of Emissions from Deforestation and Forest Degradation
RGGI	Regional Greenhouse Gas Initiative
SFM	Sustainable Forest Management
tCO2e	Tons of carbon dioxide equivalent
UNFCCC	United Nations Framework Convention on Climate Change
VER	Voluntary Emission Reduction
WRCAI	Western Regional Climate Action Initiative
WWF	World Wide Fund for Nature

Acknowledgements

This compendium has been developed through an organic process that initially led to the development of “Training modules on forest-based climate change adaptation, mitigation, carbon trading, and payment for other environmental services”. These were developed for professional and technical training, and for short courses in sub-Saharan African countries. The compendium provides the text required for effective delivery of the training envisaged in the training modules; in other words, it is structured based on the training modules. In this context many people and institutions, including those from government, civil society, academia, research, business, private sector, and other communities, have contributed in various ways in the process that culminated into the development of the compendium. We wish to collectively thank all these individuals and institutions for their invaluable contributions, given that it is difficult in such a short text to mention them individually.

We also appreciate the kind financial support received from the Government of Switzerland through the Swiss Agency for Development and Cooperation (SDC) to implement an AFF project on “African forests, people and climate change” that generated much of the information that formed the basis for writing this compendium. AFF is also indebted to the Swedish International Development Cooperation Agency (Sida) for its support of another AFF project on “Strengthening sustainable forest management in Africa” that also provided inputs into the compendium, in addition to helping facilitate various contributors in putting up this compendium. The issues addressed by the two projects demonstrate the interest of the people of Switzerland and Sweden in African forestry and climate change.

We are also grateful to the lead authors, the contributors mentioned in this compendium and the pedagogical expert, as well as reviewers of various drafts of the compendium.

We hope that the compendium will contribute to a more organized and systematic way of delivering training in this area, and eventually towards better management of African forests and trees outside forests.

Preface

African forests and trees support the key sectors of the economies of many African countries, including crop and livestock agriculture, energy, wildlife and tourism, water resources and livelihoods. They are central to maintaining the quality of the environment throughout the continent, while providing international public goods and services. Forests and trees provide the bulk of the energy used in Africa. Forests and trees are therefore at the centre of socio-economic development and environmental protection of the continent.

Forests and trees outside forests in Africa are in many ways impacted by climate change, and they in turn influence climate. Hence, African forests and trees are increasingly becoming very strategic in addressing climate change. The great diversity of forest types and conditions in Africa is at the same time the strength and the weakness of the continent in devising optimal forest-based responses to climate change. In this regard, given the role of forests and trees to socio-economic development and environmental protection, actions employed to address climate change in Africa must simultaneously enhance livelihoods of forest dependent populations and improve the quality of the environment. It is therefore necessary for Africa to understand how climate change affect the inter-relationships between food, agriculture, energy use and sources, natural resources (including forests and woodlands) and people in Africa, and in the context of the macro-economic policies and political systems that define the environment in which they all operate. Much as this is extremely complex, the understanding of how climate change affect these inter-relationships is paramount in influencing the process, pace, magnitude and direction of development necessary for enhancing people's welfare and the environment in which they live.

At the forestry sector level, climate affects forests but forests also affect climate. For example, carbon sequestration increases in growing forests, a process that positively influences the level of greenhouse gases in the atmosphere, which, in turn, may reduce global warming. In other words, the forests, by regulating the carbon cycle, play vital roles in climatic change and variability. For example, the Intergovernmental Panel on Climate Change (IPCC) special report of 2018 on the impacts of global warming of 1.5 ^{o}C above pre-industrial levels underscores the significance of afforestation and reforestation, land restoration and soil carbon sequestration in carbon dioxide removal. Specifically, in pathways limiting global warming to 1.5 ^{o}C, agriculture, forestry and land-use (AFOLU) are projected with medium confidence to remove 0-5, 1-11 and 1-5 $GtCO_2$ yr^{-1} in 2030, 2050 and 2100, respectively. There are also co-benefits associated with AFOLU-related carbon dioxide removal measures such as improved biodiversity, soil quality and local food security. Climate, on the other hand, affects the function and structure of forests. It is important to understand adequately the dynamics of this interaction to be able to design and implement appropriate mitigation and adaptation strategies for the forest sector.

In the period between 2009 and 2011, the African Forest Forum sought to understand these relationships by putting together the scientific information it could gather in the form of a book that addressed climate change in the context of African forests, trees, and wildlife resources. This work, which was financed by the Swedish International Development Cooperation Agency (Sida), unearthed considerable gaps on Africa's understanding of climate change in forestry, how to handle the challenges and opportunities presented by it and the capacity to do so.

The most glaring constraint for Africa to respond to climate change was identified as the lack of capacity to do so. AFF recognizes that establishment and operationalization of human capacities are essential for an effective approach to various issues related to climate change, as well as to improve the quality of knowledge transfer. For example, civil society organisations, extension agents and local communities are stakeholders in implementing adaptation and mitigation activities implicit in many climate change strategies. In addition, civil society organisations and extension agents are more likely to widely disseminate relevant research results to local communities, who are and will be affected by the adverse effects of climate change. It is therefore crucial that all levels of society are aware of mechanisms to reduce poverty through their contribution to solving environmental problems. Training and updating knowledge of civil society organisations, extension service agents and local communities is one of the logical approaches to this. Also professional and technical staff in forestry and related areas would require knowledge and skills in these relatively new areas of work.

It was on this basis that AFF organized a workshop on capacity building and skills development in forest-based climate change adaptation and mitigation in Nairobi, Kenya, in November 2012 that drew participants from selected academic, research and civil society institutions, as well as from the private sector. The workshop identified the training needs on climate change for forestry related educational and research institutions at professional and technical levels, as well as the training needs for civil society groups and extension agents that interact with local communities and also private sector on these issues. The training needs identified through the workshop focused on four main areas, namely: Science of Climate Change, Forests and Climate Change Adaptation, Forests and Climate Change Mitigation, and Carbon Markets and Trade. This formed the basis for the workshop participants to develop training modules for professional and technical training, and for short courses for extension agents and civil society groups. The development of the training modules involved 115 scientists from across Africa. The training modules provide guidance on how training could be organized but do not include the text for training; a need that was presented to AFF by the training institutions and relevant agents.

Between 2015 and 2018, AFF brought together 50 African scientists to develop the required text, in the form of compendiums, and in a pedagogical manner. This work was largely financed by the Swiss Agency for Development and Cooperation (SDC) and with some contribution from the Swedish International Development Cooperation Agency (Sida). In this period eight compendiums were developed, namely:

1. Basic science of climate change: a compendium for professional training in African forestry
2. Basic science of climate change: a compendium for technical training in African forestry
3. Basic science of climate change: a compendium for short courses in African forestry
4. Carbon markets and trade: a compendium for technical training in African forestry
5. Carbon markets and trade: a compendium for professional training in African forestry

6. Carbon markets and trade: a compendium for short courses in African forestry
7. International dialogues, processes and mechanisms on climate change: compendium for professional and technical training in African forestry
8. Climate modelling and scenario development: a compendium for professional training in African forestry

Another notable contribution during the period 2011-2018 was the use of the training module on "Carbon markets and trade" in building the capacity of 574 trainers from 16 African countries on rapid forest carbon assessment (RaCSA), development of a Project Idea Note (PIN) and a Project Design Document (PDD), exposure to trade and markets for forest carbon, and carbon financing, among others. The countries that benefited from the training are: Ethiopia (35), Zambia (21), Niger (34), Tanzania (29), Sudan (34), Zimbabwe (30), Kenya (54), Burkina Faso (35), Togo (33), Nigeria (52), Madagascar (42), Swaziland (30), Guinea Conakry (40), Côte d'Ivoire (31), Sierra Leone (35) and Liberia (39). In addition, the same module has been used to equip African forest-based small-medium enterprises (SMEs) with skills and knowledge on how to develop and engage on forest carbon business. In this regard, 63 trainers of trainers were trained on RaCSA from the following African countries: South Africa, Lesotho, Swaziland, Malawi, Angola, Zambia, Zimbabwe, Mozambique, Tanzania, Uganda, Kenya, Ethiopia, Sudan, Ghana, Liberia, Niger, Nigeria, Gambia, Madagascar, Democratic Republic of Congo, Cameroon, Côte d'Ivoire, Burkina Faso, Gabon, Republic of Congo, Tchad, Guinea Conakry, Senegal, Mali, Mauritania, Togo and Benin .

An evaluation undertaken by AFF has confirmed that many trainees on RaCSA are already making good use of the knowledge and skills gained in various ways, including in developing bankable forest carbon projects. Also many stakeholders have already made use of the training modules and the compendiums to improve the curricula at their institutions and the way climate change education and training is delivered.

The development of the compendiums is therefore an evolutionary process that has seen the gradual building of the capacity of many African scientists in developing teaching and training materials for their institutions and the public at large. In a way this has cultivated interest within the African forestry fraternity to gradually build the capacity to develop such texts and eventually books in areas of interest to the continent, as a way of supplementing information otherwise available from various sources, with the ultimate objective of improving the understanding of such issues as well as to better prepare present and future generations in addressing the same.

We therefore encourage the wide use of these compendiums, not only for educational and training purposes but also to increase the understanding of climate change aspects in African forestry by the general public.

Macarthy Oyebo
Chair, Governing Council of AFF

Godwin Kowero
Executive Secretary-AFF

Executive Summary

This compendium addresses the subject on the basic science of climate change: climate modelling and scenario development for professional training on forestry and related sectors in Africa.

Climate plays an important role in the socio-economic dynamics of nations, which is especially true in Africa. Climate information is crucial for a nation's socioeconomic development and planning for the future. This necessitates climate modelling, prediction and projection. This compendium is therefore a useful tool for learning about the principles involved in predicting and projecting the climate of the future.

The compendium comprises four chapters. The first chapter addresses concepts and principles of climate modelling. The second addresses aspects on modelling the climate system. Chapter three addresses climate scenario development. The final chapter is about the application of climate change modelling in forestry and related sectors.

Objective

The overall objective of this compendium is to equip the learner with skills and knowledge in climate modelling and climate change scenarios as applied in different sectors of the economy with emphasis on forestry and related sectors.

Goals

The main goal of the compendium is *"to equip the learner with knowledge and skills on how to use climate change models and scenarios applying to forestry and related sectors".* The specific goals of the compendium are to:

1) enhance the learner's knowledge on the underlying laws and structure of climate models;
2) acquaint the learner with knowledge on the structure, properties, downscaling tools, skill assessment and uses of global climate models;
3) appraise the learner with the basic concepts of climate change scenarios and applications over Africa; and,
4) familiarize the learner with tools for applying climate change modelling to forestry and related sectors.

Expected Learning Outcomes

By the end of the course, the learner should be able to:

1. Explain the fundamental concepts and principles of modelling the climate system.
2. Describe the choice, interpretation, limitations and applications of climate models.
3. Demonstrate increased understanding of climate change scenarios and the possible effects of changes in climate to forestry and related sectors.
4. Apply climate change modelling and scenario development in impact studies in forestry and related sectors.

This course is tailored for professionals in forestry and related sectors who may wish to gain some basic understanding, knowledge and skills in aspects of modelling climate and climate change. The mode of delivery for the course is through lecture notes, in-text questions and activities, exercises, self-assessment questions, and practical sessions. Please feel free to consult, and read the bibliographical material provided at the end of every lecture and internet sources.

Once again, welcome to this important compendium for professional training on forestry in Africa and related sectors.

Chapter 1: Concepts and Principles of Climate Modelling

General Objective:

By the end of the chapter, the learner should be able to explain the fundamental concepts and principles of climate change.

Scope:

- ✓ Physical models
- ✓ Types of mathematical models.
- ✓ Categories of dynamical models.
- ✓ Discretization of the atmosphere.
- ✓ Components of dynamical models

1.1 Chapter Overview

Interest in what will happen in times to come, or what the future will be like, has concerned humanity for a long time. It has manifested itself in man consulting prophets, astrologists, and forecasters in varied measures. Interest in the future has especially been aroused by impending weather. Will it be dry or wet? Is the coming season likely to be warmer or colder than the average? How will the future weather or climate affect human health? For how long will the spell of unfavourable weather last? With the advent of technology and the advancement of science, it is now possible to address most of these concerns from a scientific standpoint and state with a measure of confidence what we anticipate the future weather and climate to be like.

Expected Learning Outcomes

By the end of the chapter, the learner should be able to:

1. Describe the characteristics and properties of physical and mathematical models.
2. Discuss the categories and components of dynamical models.
3. Explain the discretization of the atmosphere.
4. Analyse the causes of uncertainty in climate models and ways of reducing the model ambiguities.

Before we delve deeper into details on modelling, let us commence our discourse by distinguishing between physical and mathematical models.

1.2 Climate Models: Definition and Types

1.2.1 Physical Models

Let us for a moment consider a toy train that resembles a real train running on rails. Such a replica would probably have properties that are similar to the actual train, such as its appearance, movement and function. We may for this reason refer to the small train as a replica, or model, of the real, big one. We may then use the model to understand the behaviour of the real train.

However, there are obviously significant differences between the replica and the real thing. For one, the difference in size implies that the properties of the two may not be identical. For example, one complete rotation of the wheels of the toy train translates to a linear distance of only a few millimetres, unlike the real train whose single revolution of the wheels would correspond to a distance of several hundred centimetres. For this reason, we must scale-down the actual train to employ the toy train.

If we intend to use the replica (toy train) to study the characteristics of the real system (real train), such as stability, safety, and aerodynamics, we may refer to the replica as a "model". Such a "model" that we can visually appreciate is an example of a *physical* model.

Important to note

A model is a simplified version of a complex system used to analyse and solve problems or make predictions.

In the example of the train model, we have already seen that there are limitations to the replica compared to the real train. Put differently, all models have limitations.

Physical models or laboratory models of the atmosphere work on the same principle. They are techniques that make use of model replicas of the observed ground surface characteristics, such as topographic relief and buildings. If we place these physical features in a chamber, e.g. a water tank or wind tunnel, we may study the behaviour of the fluid around these features and make references concerning the real atmosphere.

Figure 1 shows another way in which we can represent the atmosphere physically using a cylindrical chamber or "tank" model. This model consists of two concentric tanks of different radii. Such a model is called an *annulus* system. To begin with, we fill the space between the two cylinders with a liquid such as water or glycerine. This liquid would represent the real atmosphere. However, whereas the real atmosphere is compressible, water (or glycerine) is not compressible. We therefore expect that the physical model is not exactly identical to the real atmosphere.

We may then cause the tank to rotate about itself the way the earth does at an angular velocity, say, Ω. For the earth, the angular velocity is the circumference of the earth divided by the time it takes for it to rotate once about itself, which is approximately 24 hours per day. For the annulus, the angular velocity is the circumference of the cylinder divided by the time it takes for it to go through one complete rotation.

We can also cause "differential heating" across the fluid in the tank, i.e. we apply heat to the outer cylinder, representing the equator, and cool the inner cylinder, representing the poles. In this way, the edge would be warmer, like the equator, and inner cylinder (centre of the tank) would be cooler, like the poles. Consequently, the annulus would have the properties that are to a reasonable extent similar to what happens in the real atmosphere where the tropics are hotter and the poles colder. We can even vary the amount of heat difference between the two cylinders, and also the speed of the rotation of the annulus, and watch what happens to the fluid. When we cause differential heating and rotation, we may observe actual circulations of the fluid that are quite similar to the real circulations observed in the atmosphere. But there are fundamental differences that we must take note of.

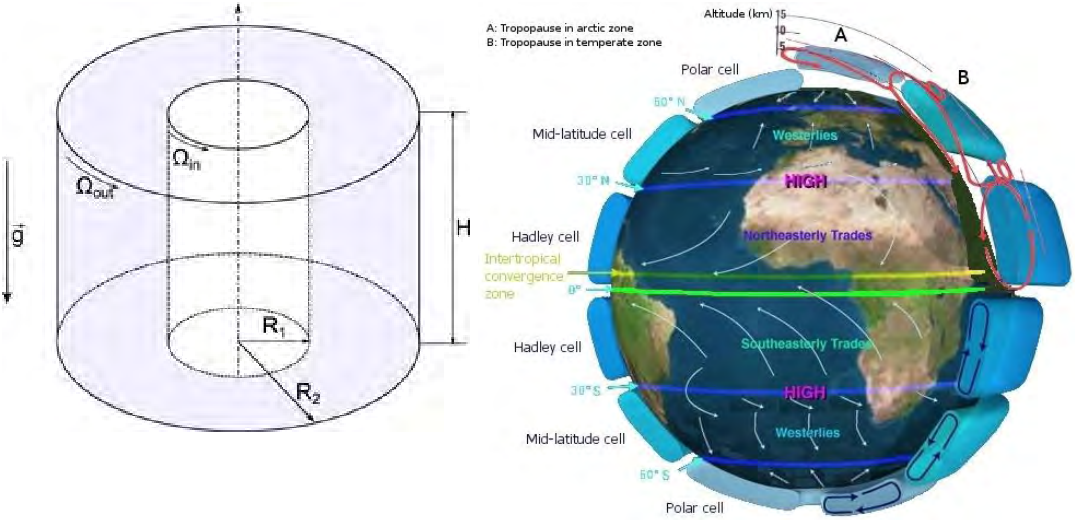

Figure 1: Annulus (physical) model of the atmosphere (left) and the real atmosphere (right). R1 and R2 are radii of two concentric cylinders with different temperature, H is the depth, and Ù is the angular velocity.

Activity 1.1

Try to identify the limitations of using a system like that shown in Figure 1 in representing the atmosphere. The solution is provided in the subsequent discussion below.

Some of the limitations of using the apparatus in Figure 1 to represent the atmosphere are presented in Table 1.

Table 1: Differences between physical models and the real atmosphere

Aspect	Real Atmosphere (Planetary System)	Physical Model (Annulus System)
1. Geometry	Spherical	Cylindrical
2. Fluid	Air	Water or glycerine
3. Temperature	Temperature is due to pressure acting on the air. This is called potential temperature	Fluid temperature
4. Compressibility	Compressible fluid	Incompressible fluid
5. Temperature changes	Heat changes occur without addition or subtraction of heat as pressure changes. These changes are called adiabatic changes	Heat changes are due to addition and removal of heat (those due to pressure changes are negligible). They are called diabatic changes
6. Flow	Airflow is due to pressure differences and the earth's rotation. This is called geo-strophic flow	Fluid motion is not geostrophic

From the table, you may have realized that although physical models of the atmosphere help us to understand the atmospheric processes, they are not exact replicas of the atmospheric system. We therefore need to take certain precautions to enable the two systems to approximate each other. To do so, we use certain dimensionless "numbers" that are obtained as ratios of certain forces (or accelerations) and have the same value in the two systems. To illustrate this point, let us consider just two of these numbers: The Rossby number (Ro) and the Reynolds number (Re).

The Rossby number is defined as the ratio of *linear acceleration* to the acceleration due to the rotation of the system, called *Coriolis acceleration*. We can express this number as follows:

$$Ro = \frac{Linear \quad Acceleration}{Coriolis \quad Acceleration}$$

On the other hand, the Reynolds number is the ratio of *inertial force* (i.e. force due to the acceleration of the motion) to the viscous force (i.e. the force arising from the viscosity or internal friction of the fluid). We can represent this number as follows:

$$\mathrm{Re} = \frac{Inertia \quad force}{Viscous \quad force}$$

From the Rossby number, the ratio of the linear acceleration to the Coriolis accelera-tion in the actual atmosphere should be the same as in the laboratory model. We call this "Rossby number similarity". In the same way, to attain Reynolds number, the ratio of the inertial force to the viscous force in both systems should be the same. We call this "Reynolds number similarity". If either of these principles is violated, the equivalence fails to hold.

From the foregoing, it is not easy to represent the real atmosphere using a laboratory model.

Activity 1.2

Attempt to explain why it is difficult to represent the atmosphere using a physical model, given that $Ro = u/\Omega d$ and $\mathrm{Re} = ud/\nu$ if u, d, í and Ù respectively represent the speed of the fluid, the distance from the boundary, the viscosity coefficient, and the rotation (angular velocity) of the system. Recall, from the train illustration, that using a physical model often necessitates having to scale-down the system.

We shall now turn our attention to the second category of models, which we call *mathematical* models.

1.3 Mathematical Models

Mathematical models are those that apply algebra (i.e. the system in mathematics where we use symbols and/or letters to represent numbers) and calculus (i.e. the mathematical system that deals with instantaneous rates of change or/and summations of continuously varying functions) with the aim of describing or clarifying phenomena.

There are three main types of mathematical models: conceptual models, empirical models and dynamical models, and combinations of these three models.

1.3.1 Conceptual Models

Conceptual models are mathematical models based on some hypothesis or theoretical idea. For example, if we can link the development of leaves on some trees, migratory patterns of insects, birds or animals; the croaking sounds of frogs, the colour of the evening sky or morning sky, etc. to impending rainfall or drought, then we can craft theoretical mathematical relationships between these observations in nature and impending floods or drought. Such relationships constitute the principle of conceptual models.

Activity 1.3

Identify examples of relationships in nature that could be classified as conceptual modes.

A more practical example of a conceptual model is in the interpretation of satellite cloud pictures. To determine what these pictures represent in terms of rainfall quantities, scientists have developed conceptual models relating the colours of the cloud features and the associated amount of rainfall, and what is producing the clouds.

Important to Note

Conceptual models are *subjective representations.* Their interpretation depends on individuals.

1.3.2 Empirical Models

Empirical models are mathematical models based on actual experimental data. We can develop empirical models for any measurable quantity. For example, we can have an empirical model to describe the vertical variation of wind, temperature, moisture or pollutants. We can also have an empirical model relating the amount of radiant heat emitted or absorbed by a body per unit area and temperature. Since these models are based on actual experimentally observed data, they are objective models; the result does not depend on the individual's judgement but on the data.

One classic example of empirical models is the category we call *statistical* models, commonly called *regression* models. If we have two variables, where one variable predicts another, and we assume the two are linearly related, we call this a *bivariate linear regression* model. Such a model has the form:

$$Y = a + bX$$

In the above expression, Y is the predictant (the quantity that is being predicted) and X is the predictor (the quantity that is predicting Y). The symbols *a* and *b* are constants obtained by empirical techniques. Sometimes the relationship also has another term representing errors in the relationship.

When we have more than one predictor, we have multivariate regression models. A *multivariate linear regression model* would have the following form, where a_i (i=1, 2, 3, …, n) are constants and X_i (i=1, 2, 3, …, n) are predictors:

$$Y = a_0 + a_1 X_1 + a_2 X_2 + \cdots + a_n X_n$$

Let us clarify a little bit more about what this expression means. Suppose we wish to predict seasonal rainfall or seasonal temperature. Seasonal rainfall and temperature depend on many factors like the amount of heating by the sun (which is called irradiance), wind regimes, sea surface temperature patterns (including slowly varying systems like El Niño and La Nina), pressure distributions (including the inter-tropical convergence zone), migratory atmospheric systems like tropical cyclones and atmospheric waves, among many others. To make our prediction, we formulate a multivariate model in which X_1, X_2, X_3, etc. are values of these factors that determine climate, and a_1, a_2, a_3, etc. are weights signifying their relative importance.

When using regression models, we should be conscious of two sources of error: *multicolinearity* and *multiplicity*. Multicolinearity is whereby the predictors are themselves strongly interrelated. For example, sea surface temperature may be related to sea-level pressure over the oceans. If predictors are interrelated the coefficients become problematic to comprehend. Multiplicity is whereby we have too many predictors from which to choose, which is accompanied with large errors. If there are lots of predictors, this enhances the chances of at least one of them to work well accidentally.

1.3.3 Dynamical Models

Dynamical models are mathematical models based on solving a set of equations which describe the dynamical and physical processes in the atmosphere. The equations are normally solved using some approximate solution technique called *numerical modelling.*

Important to Note

Global climate models are dynamical models.

We can have models that employ a combination of the above three classifications of mathematical models. e.g. we may have dynamical-statistical models, whereby dynamical outputs are used as inputs in regression models. This approach is used in a technique called *statistical downscaling* which implies making predictions at local scale levels.

1.4 Dynamical Climate Models

1.4.1 Categories of Dynamical Climate Models

We have four basic categories of dynamical models. These are specialized models, mesoscale models, regional models, and General Circulation Models (GCMs).

Suppose we want to model, dynamically, the movement of air to determine the cause of Carbon or dust particles in our rain water. Or perhaps there is too much turbulence at an airport, or unusual smog, and we wish to give a reasoned forecast to the aviators. Or, we wish to predict the state of the ocean to inform the seafarers. Such dynamical models are termed as specialized models, since they are intended to address a specific application. Specialized models are also called *application* models.

If, on the other hand, we wish to model the manner of the flow of air and the resulting precipitation over a locality caused by local (i.e. mesoscale) systems like lakes, mountains, forests and cities, especially those circulations induced by thermal differences, we refer to such models as mesoscale models. These are formulated over small spatial extents in the order of tens to hundreds of kilometres wide.

Conversely, we may wish to model processes that occur over a fairly large region in order to account for synoptic (i.e. birds eye-view) systems that contribute to the observed weather. Dynamical models that are able to capture the state and behaviour of the atmosphere over a relatively large region used for daily weather forecasts are referred to as operational synoptic models or regional models. These models may also be used for modelling the regional climate. The domain covered by such models may be global or regional.

GCMs are dynamical models of atmospheric flows that run for a long *time* over a large *area* of the earth's surface. Because of the spatial and time scale, they simulate the mean climate over the entire globe or hemisphere. For this to happen, GCMs include sufficient energy (thermal forcing) and frictional effects that enable them to run for a long period and to simulate the mean climate. In a restricted sense, GCMs may also be called global climate models.

Activity 1.4

Explain how the four categories of dynamical models work.

Let us now turn our attention and see how and why the atmosphere is formulated in dynamical modelling.

1.5 Discretisation of the Atmosphere

Being a continuous entity, the atmosphere must be "discretised" before the model equations can be applied to it. To do so, we divide it into finite "boxes". Alternatively, we may consider the atmosphere as a large system whose elements vary as in a wave. In the first approach, we use the "grid-point" methodology. In the second, we use spectral techniques.

What is grid box discretization? In "grid point" models, we divide the atmosphere into a mesh of cubical volumes or parcels of atmosphere called *grid boxes*, with the centre of each box called a *grid point.* We then define our dependent variables at these grid point locations. When we define a variable at a grid point, it represents the information in the entire grid box.

When we use grid boxes, we then have grid sizes. The *grid size* is the distance between two grid points (i.e. the distance between the centres of two grid boxes). It is also called the grid length, grid spacing, and grid resolution or grid increment. More practically, grid size refers to the dimensions of the grid boxes. A simple illustration of a discretized atmosphere is illustrated in Figure 2.

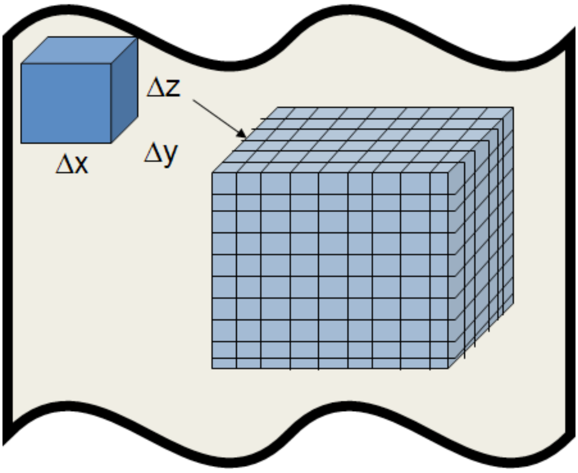

Figure 2: Illustration of a domain with a discretized atmosphere. A continuous atmosphere is redefined by a cubical volume which is subdivided into grid boxes with dimensions in the x-, y-, and z-directions. Notice the equal horizontal dimensions but variable vertical spacing with higher resolution near the surface, decreasing upward.

Grid sizes are sometimes measured in units of degrees or minutes. Figure 3 shows typical 10-degree (1110 km) and one-degree (111 km) grid resolutions over Africa. As we reduce the coarseness to resolve most features of the general circulation, we also increase the usage of computer time. More recent GCMs employ resolutions of twenty-seven minutes (50 km), thirteen and a half minutes (25 km), or even smaller horizontal grid spacing!

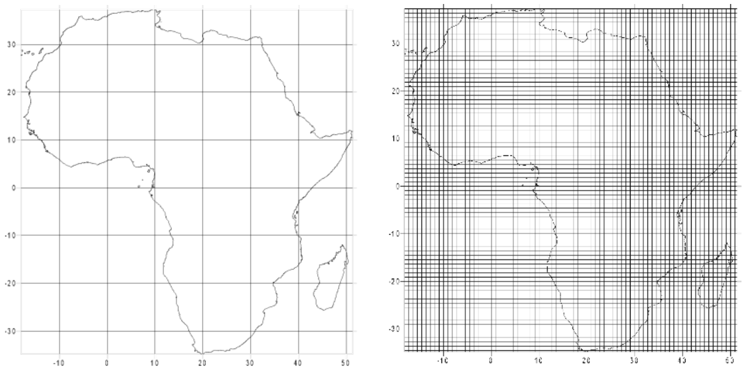

Figure 3: Examples of grid resolution over Africa (10° x 10°, and 1° x 1°; we can similarly illustrate for 0.5° x 0.5° spacing, or smaller). Higher resolution requires more computational resources.

Although the discussion above centres on horizontal resolutions, we also have vertical levels. Fewer grid boxes are applied vertically because of lesser dramatic variations in the vertical directions as happens on the surface, except in the boundary layer and the cloud layers.

How grid points are used in dynamical climate models? In a discretized atmosphere, grid points are the points of reference at which the atmospheric variables are computed.

Important to Note

A dynamical climate model is a mathematical description of the earth's climate system that is represented using an array of regular grid points in the horizontal direction but with multiple levels in the vertical direction.

For each grid box, the model solves the large-scale behaviour of atmospheric quantities. The distributions in space and time of these quantities are called *budgets*. E.g. we have the budgets of momentum (i.e. movement), energy (i.e. heat), and mass (specifically humidity). These quantities are described using the equations of the physics of motion, heat and its transfer, and moisture. In effect, the complex physical processes that take place on smaller spatial scales than the model grid are accounted for, as well as surface features like ocean-continental differences (which we call land-water mask), mountains and valleys and other forms of terrain undula-tions (called orography), and surface characteristics like vegetation (specifically forests), and albedo. Resolving these processes is termed as parameterization.

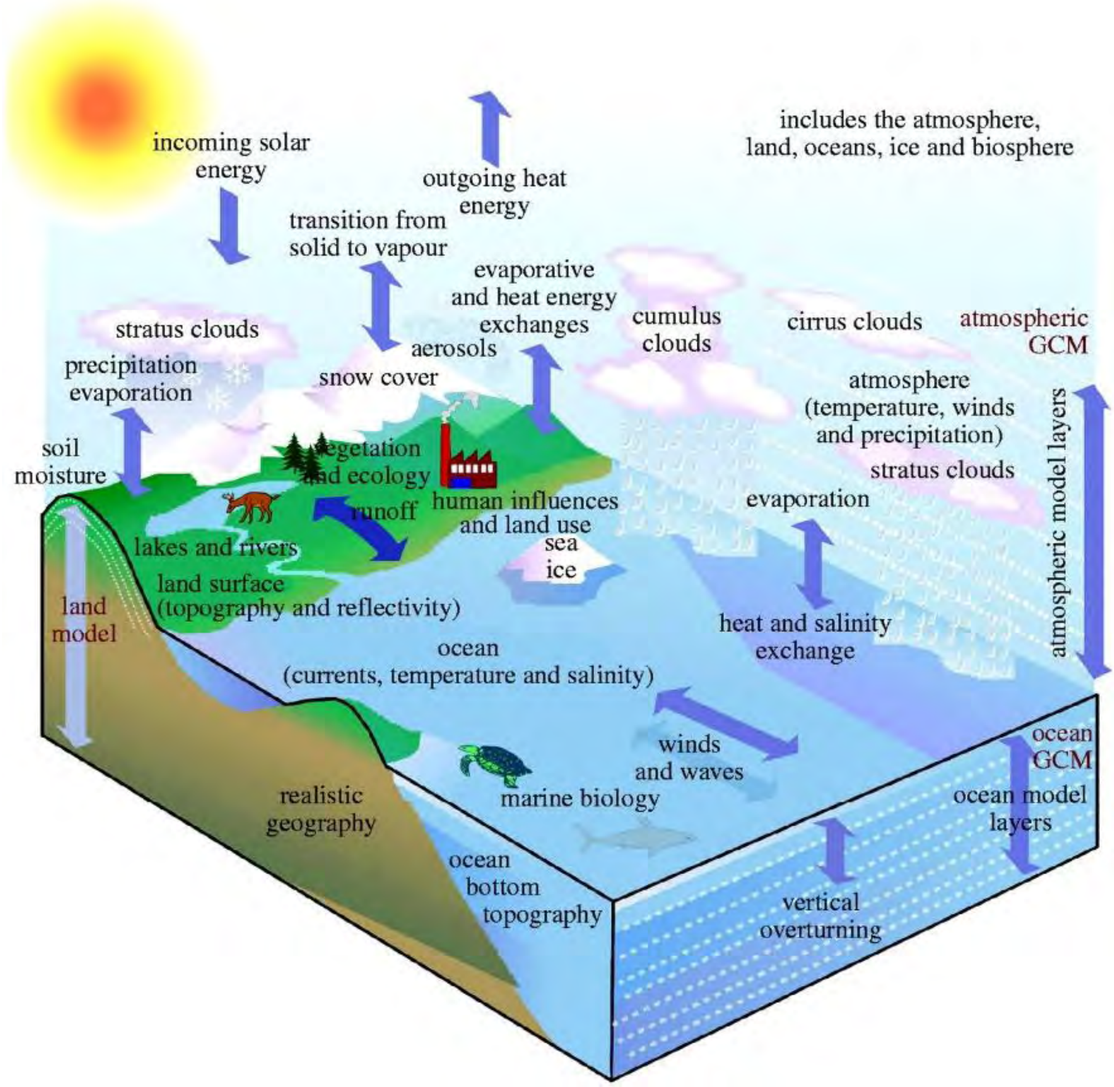

Figure 4: An example of processes of the climate system that dynamical models attempt to represent. Illustration from the NCAR community climate system model (http://rsta.royalsocietypublishing.org/content/367/1890/833)

Figure 4 above shows schematically an example of the processes of the climate system that dynamical models attempt to represent.

We shall now turn our attention to the components of dynamical models.

1.6 Components of Dynamical Models

Dynamical models generally consist of *four* major components. These components are the model dynamics, the method of solution, the boundary conditions, and the model physics. We shall study each one of these components in this section. First, there is the aspect of model dynamics.

1.6.1 Model Dynamics - Conservation Laws

The term “model dynamics” refers to the set of equations that drive the entire model. These equations are termed as governing equations or hydrodynamical equations. If these equations are to be solved, they should form a “closed” set. Closure means that the number of unknowns should be equal to the number of equations (it is worth noting that if the number of unknown quantities exceeds the number of equations, the equations cannot be solved). The equations are based on conservation principles, and include equations that represent the conservation of mass, heat, movement (or momentum), and moisture, as well as the equation for ideal gases (which we also call the equation of state).

Important to Note

Conservation of mass, energy and momentum mean that, over a long period of time, mass, energy, and momentum remain constant globally.

The governing equations vary with time (t) in the form given below, where Q represents any field variable like temperature, wind velocity, moisture, etc. while S originates from (the sources) or goes to (the sinks).

$$\frac{dQ}{dt} = S$$

The above ordinary differential equation is normally expressed as a *partial differential equation*. In these equations, “partial” variations are possible in each direction in space and time, while holding the other directions as constant. These equations have the form below:

$$\frac{\partial Q}{\partial t} + u\frac{\partial Q}{\partial x} + v\frac{\partial Q}{\partial y} + w\frac{\partial Q}{\partial z} = S$$

You may have noticed that the total derivative in the first equation d/dt has now been expressed as a sum of partial derivatives in time at a locality ($\partial/\partial t$) as well as in the east-west or x-direction ($\partial/\partial x$), north-south or y-direction ($\partial/\partial y$) and vertical or z-direction ($\partial/\partial z$) with corresponding “advection velocities” in these directions given by u, v and w. Advection means that there is transfer without changing the internal properties of any given quantity. The conservation principles differ in the details of the source term S.

Conservation of Mass: The Continuity Equation

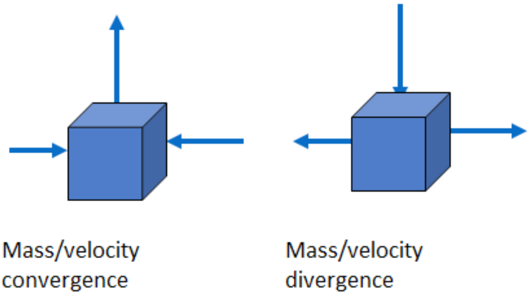

Figure 5: The principle of the conservation of mass. Mass convergence is associated with upward flow of air; mass divergence with downward flow of air

What is the conservation of mass? It is based on the principle of indestructibility of matter. This principle states that matter is neither created nor destroyed, and that the rate of change of mass at a locality depends only upon the net horizontal mass inflow (which is called convergence) or outflow (which is called divergence) and vertical motion (Figure 5 above). This law is sometimes called the *continuity* equation.

Conservation of Heat: The Thermodynamic Equation

What is conservation of heat? It is based on the first law of thermodynamics which states that heat changes within a system causes a change in its internal energy and does external work. Put differently, this principle states that the rate of change of energy in a system is governed by the transfer of energy across the boundaries of the system (Figure 6). The transfer of energy may be in the form of radiation, convection, or conduction. This law is sometimes called the thermodynamic equation.

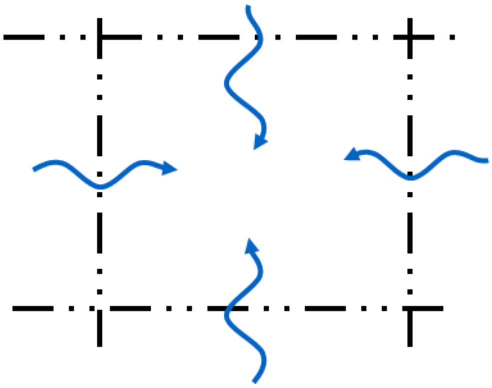

Figure 6: The principle of conservation of energy showing heat transfer across the boundaries of a system which causes changes in the temperature of the system.

Conservation of Momentum: The Equations of Motion

What is the conservation of momentum? It is based on Newton's second law of motion which states that the rate at which the momentum of a moving body changes is proportional to the sum of the forces that bring about the motion and acts in the direction of this force. The conservation of momentum principle as applied to the atmosphere is founded upon the fact that the acceleration of air parcels depends on the pressure gradient force which is brought about by differences in pressure on earth; the Coriolis force which arises due to the rotation of the earth; the gravity force which is due to the gravitational pull on the atmosphere by the earth's mass; and the frictional force which is due to the roughness of the earth's surface as well as internal friction of the fluid. This principle is represented in three dimensions: east-west, north-south, as well as vertical directions. This set of three equations is sometimes referred to as the equations of motion.

A special case of the momentum equation in the vertical direction constitutes the hydrostatic balance which illustrates a balance between buoyancy and gravity forces. In large-scale flows, vertical acceleration is negligible, and the pressure gradient force (buoyancy) and gravity force balance each other exactly (Figure 7). This equation is called the *hydrostatic balance* equation or *hydrostatic equilibrium*.

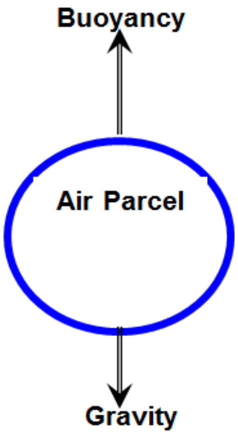

Figure 7: The hydrostatic balance which is valid for frictionless and non-accelerating large-scale flows

Conservation of Moisture: The Humidity Equation

What is the conservation of moisture? The conservation of water substance is based on the fact that water changes its state depending on its temperature, whether in liquid, solid and gaseous states; this equation is also called the *moisture* equation. The moisture is normally "parameterized" (i.e. quantified, mathematically) in model physics, and so the moisture equation is not used in this sense.

Ideal Gas Law: The Equation of State

What is the ideal gas law? The final equation in this set of equations is called the equation of state which supposes that the atmosphere behaves approximately as an ideal gas and hence it obeys Charles' law and Boyle's law exactly, hence we also term it as the ideal gas law. This equation relates pressure, density and temperature.

Having discussed the equations that constitute the model dynamics, we shall now turn our attention to the methods used to solve these equations.

Method of Solution

What is a method of solution? Model equations are usually based on differential principles that presuppose that the elements vary continuously in time and space. In reality, the observed variables are defined at finite points in space and time. These points are called grid points. Hence, the equations require special techniques to solve them.

A method of solution refers to the technique of integrating (i.e. projecting by summing up) the governing equations in time to obtain the future distribution of the field variables in time and space. Two most commonly used methods of solution are *finite difference* methods and *spectral* methods. The first employ data at grid points and the second suppose that atmospheric phenomena vary in a wavy manner.

Finite Difference Techniques

What is the principle of finite difference methods? We have already seen that the equations governing atmospheric behaviour are based on calculus and algebra. We have also learned that the continuous atmosphere is first discretized in the model atmosphere by dividing it into a large finite number of discrete points, called grid points, before we can apply our equations. The discrete points are the basis for the finite differencing method.

In calculus, the governing equations are written as *differential* equations which are where we relate physical quantities with their rates of change in both time and space. The rates of change are called *derivatives*. The physical quantities are called *functions*. The differential equations therefore show the relationship between a given physical quantity or quantities (or function(s)) and its derivative(s) that change in time and space.

When the differential equation relates a physical quantity (or function) and a single derivative, we call it an *ordinary* differential equation. For example, suppose the motion of a particle of mass m is constrained by the relationship between the displacement of a body, x and the time, t, of an object under the force, F. We can express this relationship in calculus as follows:

$$m\frac{d^2x}{dt^2} = F$$

Doubtless, the force, F, and position x, vary in time. The above equation is in fact the famous statement of Newton's second law of motion, where the acceleration is given by the expression:

$$\frac{d^2x}{dt^2} = \frac{d}{dt}\left(\frac{dx}{dt}\right).$$

When, on the other hand, a physical quantity depends on a multiplicity of unknown variables (i.e. several derivatives), we call the differential equation a *partial differential equation.* For instance, a quantity Q that varies in time t, but also in space x (here we use the x-direction for illustration purposes, but the variation is also in the y- and z-directions) may be stated as below where c is a constant "advecting velocity":

$$\frac{\partial Q}{\partial t}+c\frac{\partial Q}{\partial x}=0$$

It should be noted that the total derivative d/dt has now been replaced by partial derivatives ∂/∂t and ∂/∂x.

When we apply the finite difference technique, we express the partial differential equations as finite differences. To illustrate this concept, we may express the above equation in finite difference form as:

$$\frac{\partial Q}{\partial t}+c\frac{\partial Q}{\partial x}=\frac{Q(t+\Delta t)-Q(t-\Delta t)}{2\Delta t}+c\frac{Q(x+\Delta x)-Q(x-\Delta x)}{2\Delta x}+\varepsilon(\Delta t,\Delta x)$$

In the above equation, we have replaced the *differential* terms (terms on the left hand side) with *difference* terms (terms on the right hand side), and introduced Δt, which is a *time step*, and Δx, which is the grid spacing in the x-direction. The last term ε(Δt, Δx), is an error term called the *truncation error*. The truncation error is the error that arises when we replace differential terms with finite difference terms; i.e. it is the difference between differential terms and difference terms in our equation. You may have noticed that the error arises in terms of time differencing (Δt) and space differencing (Δx).

When we make $Q(t+\Delta t)$ the subject by equating the right hand side of the above equation to zero, we may determine Q at a future time Δt. If we omit the error term ε, the equation would look as below:

$$Q(t+\Delta t)=Q(t-\Delta t)-c\frac{\Delta t}{\Delta x}\left[Q(x+\Delta x)-Q(x-\Delta x)\right]$$

Let us make one more point on finite differencing. To obtain solutions that are reliable, the error should be as small as possible. For this to happen, the time step Δt, and grid spacing Δx should be as small as possible. This means that grid boxes should be infinitesimal and the time interval should be small. But if these quantities are very small, it would mean that the amount of computer resources used would be high. So we must balance between minimizing the error, and sparing the computer resources.

The second point is: erroneous solutions should not travel by more than one grid spacing in space in a given time interval. In other words, the time step should be less than Δx/c. This condition is called the *Courant-Friedrich-Levy* criterion.

This is the basic principle of prediction by the finite difference methods.

Spectral Methods

What are spectral techniques? They are an alternative method for solving differential equations numerically. This method assumes that atmospheric phenomena vary as waves. For this reason, the mathematical procedures used in spectral methods are more engaging than those for finite differencing schemes, but let us mention briefly the underlying principles.

In the spectral technique, we express the differential equations as a sum of certain functions that represent specific envisaged motions e.g. wave motion. When we apply spectral methods to solve time-dependent partial differential equations, the solution is typically written as a sum of terms called coefficients representing waves that vary in time. When we substitute these coefficients in the partial differential equations, it yields a system of ordinary differential equations in the coefficients which can be solved using any numerical method for ordinary differential equations.

The advantage of spectral methods is that they represent velocities accurately. The disadvantage is that the computational resources required are much larger than for equivalent finite difference methods.

So far we have studied two components of all dynamical models. We now focus on the third component which is boundary conditions.

1.6.2 Boundary Conditions

What are boundary conditions? The phrase *boundary condition* is used to refer to values specified at the start of a model run and at the perimeters (boundaries) of the model domain. Boundary conditions are of two types: Temporal boundary conditions and spatial boundary conditions.

Temporal Boundary Conditions

What are temporal boundary conditions? Essentially, modelling involves determining a future state of the atmosphere. To do so, we require current or past information at the start of the model run. These values may be current or past observed values or values obtained from a previous forecasted state of the atmosphere. These values are called initial conditions or *temporal* boundary conditions.

Because the initial state of the observed or modelled atmosphere more often than not has errors, the initial values should first be “cleaned up”. Cleaning up necessitates first carrying out a quality control exercise on the raw data, where outliers are removed and missing information estimated and filled in.

What is initialisation? Following the clean-up exercise on the data, we may still have errors that may amplify with time leading to instability in the modelling process. This is because the available data may not be in balance (i.e. in agreement) with the model equations, and must be adjusted accordingly so as to agree with the equations. This adjustment process is termed as *initialization*.

Important to Note

Initialization is the process of determining the values of dependent variables required to commence the integration by modifying the initial data to remove errors that would otherwise give rise to unwanted instabilities.

What is objective analysis? Since we need the initial information at specific points, it is essential that this data is interpolated or extrapolated to grid points. The process of interpolating data to specific points is termed as *objective analysis.*

What data assimilation? Often we require updating the initial data used in the model forecast to improve the accuracy of the forecast. We achieve this by “blending” the actual observations and the model output (or background field) to create the best possible model analysis at the start of the new forecast. This is called *data assimilation*. Put differently, data assimilation is the process of finding the model representation which is most consistent with the observations.

Activity 1.5a

Explain why data assimilation is done together with initialization.

Spatial Boundary Conditions

What are spatial boundary conditions? A domain of integration is defined in dynamical models because of constraints in computational resources. More often than not it is important that information moves in and out of our domain. This information flow is useful because the atmosphere has no boundaries, and whatever happens in one part affects other parts. But it is equally important to control and even limit the flow of information across our boundaries because of the danger of external information spuriously contaminating the solutions inside our domain of interest. For this reason, we must set the acceptable values at the periphery of the model domain. These values are called *spatial* boundary conditions.

Important to Note

Spatial boundary conditions are values at the perimeter (boundary) of the domain of integration.

Since our domain over which modelling is done is cuboid in shape, we have to define our boundary conditions in the lateral and vertical directions.

What are lateral and vertical boundary conditions? Lateral boundary conditions are values imposed on the lateral perimeters of the domain of integration. They are only applied to limited area models (LAMs) since the lateral boundaries in GCMs are assumed to be cyclic.

Vertical boundary conditions are conditions imposed at the top and bottom of the model domain. In GCMs, the top is placed at the top of the atmosphere, where pressure is zero.

The nature of the surface at the base of a model domain can dramatically affect the air column above it. It is therefore essential that a numerical model of the atmosphere accurately specifies the surface of the earth. The characteristics that define the bottom boundary include orography (terrain undulations, mountains, and hills), lakes, oceans, vegetation (especially forest cover), type of soil, soil moisture, snow cover, sea surface temperature, sea ice, and so on. The bottom boundary unlike the top and lateral boundaries has physical significance.

Activity 1.5b

Besides the bottom boundary, all the other boundaries in dynamical models are used for computation convenience. Explain why the bottom boundary is crucial in dynamical modelling of climate.

1.6.3 Model Physics: Parameterization of Physical Processes

We mentioned earlier that subgrid-scale physical processes (i.e. process that occur on scales that are much smaller than the grid spacing of the model) are represented by mathematical expressions based on certain assumptions, called *parameterization.* Processes parameterized include radiation, convection, turbulence, gravity waves, and precipitation.

Radiation is computed separately as solar radiation and infrared (terrestrial) radiation. Computation of radiation takes a lot of computer resources.

Fluxes (i.e. transports) in the earth's boundary layer (i.e. the lowest layer of the atmosphere) and the processes on the earth's surface and soils have to be computed. Fluxes of heat, moisture and momentum occur through turbulent (i.e. irregular and unpredictable) exchanges in the boundary layer of the atmosphere and in the soil layers.

Precipitation and especially rainfall is one of the most important products in a climate model, especially in the tropics. For accurate forecasts, the computation of all processes leading to cloud and rainfall formation should be computed accurately.

Another aspect that should be computed correctly in dynamical models is mountain effects. Mountains block the flow of air, forcing it to ascend over it, which causes rainfall formation; this is termed as *flow-blocking*. Mountains also distort the flow, causing it to slow down, "vibrate" on the opposite side, and form small turbulent eddies. We call this *gravity-wave drag*. Flow blocking and gravity wave drag should be represented correctly at the bottom boundary.

We shall now turn our attention to model uncertainties.

1.7 Uncertainties in Climate Models

What causes uncertainties in model outputs? Uncertainty refers to the inherent errors that amplify with time and reduce the accuracy of models. To reduce such errors, we may use ensemble prediction systems or sensitivity testing approaches.

Activity 1.6

Explain why we would not expect climate models to be perfect representations of the warth-atmosphere system.

1.7.1 Causes of Uncertainties in Model Outputs

Uncertainties may result from various causes. One type of uncertainty (which for convenience we shall term Type 1 uncertainty), is where there are errors in the initial state (or conditions) in the model run. Initial conditions in dynamical models may be derived from GCMs or from observations, or both. Because none of these initial states are fool proof, uncertainties in observing them lead to uncertainties in pre-dicted values. This introduces errors, called *initial-state* errors.

A second type of uncertainty (Type 2 uncertainty) is whereby errors or inaccuracies exist in our representation of the system. Errors in dynamical models arise from two main sources. First, we have the effects of numerous phenomena with scales smaller than the model grid scale, such as clouds, often called subgrid-scale phenomena which are overlooked. As we stated previously, these phenomena are parameterized. Parameterization introduces errors in the final results.

When running climate models, we have to make choices on which parameterization schemes to employ to represent the physical processes (e.g. radiation, convection, cloud schemes). Forecasts from the same model and same initial state may give different forecasts when different schemes for the physics are used, because of the arbitrariness in the choice of such schemes.

Secondly, components of models for calculating different processes in various subsystems are commonly developed independently, while assuming that the other components are well represented. For example, in a model for the atmosphere and a model of the ocean, developers of one assume that the other is perfectly known. When these models are coupled (i.e. used together), errors arise. We shall call these two sources of inaccuracies *model structure errors*.

A third type of uncertainty (Type 3 uncertainty) is where there is uncertainty in the evolution of the system. This is where unexpected occurrences happen between the start of the model run and its completion. To illustrate this point, suppose that a tropical cyclone suddenly begins forming outside of our model domain after the start of the run, the system would alter the behaviour of the winds (the momentum budget), the heat distribution (the energy budget) and the moisture patterns (the humidity budget) within our domain of interest. In other cases, we could have changes in other drivers of the climate system like the atmospheric composition, sea-surface temperature, etc. Such unexpected occurrences alter the results. We may refer to this effect as *model evolution* errors. We shall combine Type 2 (model structure errors) and Type 3 (model evolution errors) and call these *model uncertainty*.

We shall now turn our attention to the underlying principles of ensemble prediction systems.

1.7.2 Ensemble Prediction Systems

How do we deal with model uncertainties? Model formulation uncertainties may be addressed by using ensemble prediction systems (EPS). EPS are of four types, which are discussed below.

Model formulation uncertainties may be addressed by stochastically perturbing model variables (and/or tuneable physics parameters) as the model runs. When we average these outputs for a single model, we call this a *single model ensemble,* which typically make use of different initial conditions for the same physics scheme.

Alternatively, we may combine the ensembles from different modelling centres where each modelling centre supposedly uses different model physics. We refer to this as multi-model ensemble. *Super ensemble* forecasting are multi-model ensembles for which the different models are adjusted for their various biases. Where different physical processes are combined, e.g. combinations of atmospheric, ocean and wave models, we call these Hyper ensemble forecasting.

1.7.3 Sensitivity Testing Approaches

In dealing with uncertainty, we may use ensemble approaches. Another way of dealing with uncertainty is by using sensitivity analysis. In this approach, one tries to determine the sources of uncertainty in the model inputs and structure through varying inputs or methodologies. This may include changing the model domain, model resolution, physics schemes, advection schemes, and different parameters, which is usually done in an academic (rather than operational) setting. The contributions and hence importance to the final result of various inputs or techniques are then identified.

Sensitivity analysis is done for several reasons. Among these are:

1) To check for the strength of the result of the model in the manifestation of uncertainty.
2) To decrease the time wasted in focusing on sensitive parameters through calibrating models.
3) To detect inaccuracies in the model by exploring unanticipated associations between model inputs and model outputs.
4) To lessen uncertainty through detecting the inputs of the model causing the uncertainty in the model output.
5) To make models simpler by removing inputs or unnecessary parts in the structure of the model that do not influence the output.
6) To make the results better, and therefore, more dependable, comprehensible, convincing and believable to decision makers.
7) To raise the appreciation of the interactions between the output and the input variables in the model.

Shortcomings can arise in sensitivity analyses in several ways, for example:

1) If the inputs into the model depend on each other; for instance, rainfall depends on winds.
2) If the interaction of the inputted variables is such that altering at least two inputs changes the output significantly, in comparison to the change in the individual inputs. For example, altering the horizontal velocity components can markedly alter the vertical velocity.
3) If the model has many uncertain inputs and improvement of the output of one parameter, e.g. temperature, may misrepresent other parameters, e.g. rainfall.
4) If the response of the model to the inputted parameters does not show a pure linear one-to-one relationship.
5) If, like in hard-wired models, it may be difficult or impossible for the modeller to affect the input data or modify the setup of the model.
6) If the model runs are too time-consuming.

Activity 1.7

1. Demonstrate the need for ensemble prediction in dynamical climate modelling.
2. Outline the reasons why it is necessary to perform sensitivity testing on models.
3. What are the limitations of sensitivity testing of dynamical climate models?

1.8 Summary

Dynamical climate models are mathematical descriptions of the climate system of the Earth represented using horizontal grid points but with multiple vertical levels. Dynamical models include GCMs, regional models, mesoscale models, and specialized models. Dynamical climate models constitute model dynamics, method of solution, boundary conditions, and model physics. The model dynamics is based on conservation principles: the conservation of mass, heat, momentum, and moisture, and assume the atmosphere is an ideal gas. These equations are normally expressed as rates of change, or derivatives. Model equations are solved using finite difference methods that employ data at grid points, and spectral methods that suppose wavy behaviour of atmospheric phenomena. Boundary conditions are specified for every grid box at the start of a model run, as well as at the bottom, top and lateral perimeters of the model domain. Physical processes that occur on subgrid scales, including radiation, convection, turbulence, gravity waves, and precipitation, are estimated using a mathematical technique called parameterization. Inaccuracy occurs in forecasts because of errors in the initial data, and errors in the models/modelling system, i.e. misrepresentation of the climate system and its evolution. Model uncertainties are addressed by using averaging techniques called ensemble prediction techniques, and sensitivity tests

1.9 Self-Assessment Questions

Activity: Self-Assessment Questions

1. Distinguish between dynamical and statistical modelling; physical and mathematical models.
2. Explain the meaning of the terms model domain and boundary, grid point, forcing.
3. What is a dynamical climate model?
4. Describe briefly the general architecture of climate models.
5. Define the terms GCMs, regional, mesoscale, and specialized models.
6. Name 4 categories of dynamical models and 4 components of dynamical models.
7. Distinguish between model dynamics and model physics.
8. Explain how finite differencing techniques differ from spectral techniques.
9. State the principles upon which model dynamics is grounded.
10. Explain why the bottom boundary is the most important in a dynamical model.
11. Distinguish among objective analysis, data assimilation and model initialization.
12. Describe how models are defined at their lateral perimeters, and the top.
13. Name the physical processes that are modelled in dynamical models.
14. State the causes of uncertainties in model outputs.
15. Explain two ways of minimizing uncertainty in dynamical models.
16. Discuss four types of ensemble prediction systems used in climate prediction.

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Chapter 2: Modelling the Climate System

General Objective:

By the end of the lecture, the learner should be able to describe the choice, interpretation, limitations and applications of climate models.

Scope:

- ✓ Design and selection of dynamic models
- ✓ Scaling down GCM data to smaller locations
- ✓ Methods os assessing the quality of model data
- ✓ Applications of climate model data

2.1 Chapter Overview

In the previous chapter, we learned that climate models are mathematical represent-tations of the climate system of the earth-atmosphere system, defined on a regular horizontal grid-point array and several vertical levels. At each grid-point, the model solves the large-scale budgets of airflow (momentum), heat (energy) and moisture (matter), based on non-linear equations of the physics of the atmosphere, and touching on motion, mass, thermodynamics and irradiative transfer, accounting for the many complex physical processes that take place on smaller spatial scales than the model grid, while taking cognizance of surface features, like ocean-land areas, topography, and surface characteristics, like vegetation and albedo.

Expected Learning Outcomes

By the end of this chapter, the learner will be able to:

1. Describe the structure and examples of GCMs.
2. Explain the rationale and principles in statistical and dynamical downscaling of GCM data.
3. Discuss some of the main tools of evaluating the quality of climate model data.
4. Describe the applications and uses of data from climate models.

We shall begin our discussion by examining how we may choose the models for our use.

2.2 Design of Climate Models

2.2.1 Simulation, Prediction and Projection

In selecting a model for our use, we need to know what we wish to use it for. To this end, we need to define terminologies sometimes used incorrectly: climate simulation, climate prediction and climate projection.

In etymological terms, the word *simulate* comes from a Greek word that is also the root for the word *similar*, and basically means to model, mimic or imitate. We use the term *climate simulation* if our interest is to mimic or replicate the future state of climate using a model, but typically *starting from an arbitrary or mean state*. In this case, the model represents the atmospheric system and the simulation imitates its evolution over time.

The second word, *predict,* literally means telling the future in advance. When we apply a dynamical model to guess or foretell the future state of the atmosphere *starting from a known observed state*, we call this process *prediction* or *forecasting*.

Our third word, *projection,* means *representation*. If we start from a mean state but seek to guess the future state of climate using a model driven by an *idealized* forcing scenario, e.g. an irradiative forcing scenario or land-use/cover change, we call this climate *projection*. Climate scenarios are thus not predicted, but can be simulated.

Activity 2.1

Why is it difficult to predict the climate of a place for the next several decades?

We now turn our attention to the category of models called GCMs.

2.2.2 GCMs: General Circulation Models or Global Climate Models?

What is a GCM? In the previous chapter, we defined four categories of dynamical models. We referred to one category as GCMs. Let us delve a little bit more into this category of models.

A numerical model of atmospheric flows that includes sufficient thermal forcing and frictional effects which enables it to run for a long period thereby simulating the mean climate is termed a GCM. Since GCMs basically model the global climate, the abbreviation GCM may also be used in reference to *global climate models*.

GCMs generally cover the entire globe, a hemisphere, or a large part of the globe. GCMs that emphasise physical and thermo-dynamic developments in oceans and their interaction with the atmosphere are termed oceanic GCMs (or OGCM). Those GCMs that do not focus on the intricate thermal, dynamic and physical processes within the shallower and deeper ocean basins but incorporate land surface processes and their interaction with the atmosphere are termed atmospheric GCMs (or AGCM). When the two are used together, we call this practice *coupling*. Coupling enables us to give emphasis to complex features and processes within the oceans that affect atmospheric flows, like sea surface temperature and sea-ice, and developments on land, such as evapotranspiration. We call such a system a coupled ocean-atmo-sphere general circulation model (AOGCM) or coupled general circulation model (CGCM).

We have already made mention of the fact that the term global climate model refers to a GCM used for simulating the global climate, hence GCM may also mean global climate model. However, a global climate model may also refer to a system of tools that incorporates other components for modelling climate, in addition to a general circulation model. Alternatively, GCM may refer to a category of tools that employ various means for modelling climate, besides GCMs.

In this work, global climate models refer to GCMs; the two terms are used interchangeably. Being dynamical models, GCMs are based on the four components discussed in the previous chapter. In addition, GCMs have certain basic properties discussed below.

Activity 2.1

1. Describe the four components of all dynamic models.
2. In your opinion, should dynamical climate models be referred to as GCMs or global climate models? Provide a justification for your answer.

2.2.3 Properties of GCMs

What are some of the properties of GCMs? First, we need to appreciate that GCMs are coarse models. This means that the grid spacing (grid boxes) in GCMs is much larger than in LAMs. Being global in nature, a finer resolution would take too much computational time to run. When GCMs were first used, the grid spacing was in the order of 5° (more than 500 km). Currently, because of advances in computational capabilities, scientists are experimenting on global models with horizontal resolutions of 0.1° (c. 12 km)!

Secondly, GCMs are designed to describe the general behaviour of the atmosphere. They give the general "direction" of atmospheric quantities without providing the details. Thirdly, GCMs simulate seasonal and annual cycles to detect climate variability, and in some cases, climate change. However, GCMs do not simulate weather, unless they are used to drive a regional synoptic model through dynamical downscaling. We shall see how this is done later in this Chapter.

2.2.4 Components of Climate System Drivers in GCMs

How do we incorporate components of the climate system into GCMs? You may recall from earlier studies that the climate of a place depends on the interaction of global features and local characteristics. These properties are governed by certain physical features in the earth-atmosphere system.

By their nature, GCMs are designed to obtain information from the ocean and pass it on to the atmosphere, but sometimes they may also be designed to pass the information from the atmosphere back to the ocean, in an interactive nature. We call this "two-way interaction". Coupling of GCMs with the upper layers of the oceans ensures that when the ocean parameters change, the atmospheric response is detected. When GCMs are used for climate studies, it is very important that they take into account all the components of the climate system (Figure 8). These components are the atmosphere, the land surface (which includes the hydrosphere), the biosphere, the ocean, and the cryosphere. Let us study these processes briefly:

1) In considering the atmosphere, we need to take cognizance of the constitution of the gases therein. Whereas the atmosphere is made up of different permanent gases like Nitrogen, Oxygen and the inert gases including Argon, our interest is in those atmospheric gases that vary in their concentration and amount and that may change the heat budget and modify the climate, which we call greenhouse gases (GHGs).

Important to Note

Gases have a response time in the order of one month (τ ~1 month).

2) The structure of the land is a primary determinant of the weather and climate of a place. The characteristics of the physical surface - mountains, the land structure, lakes, rivers, ground water, forests, type of soil, urban areas, etc. - that influence the atmospheric circulation should be incorporated into the model to be able to resolve smaller-scale features. However, in GCMs only large scale features are considered. Features of smaller scales are incorporated as subgrid-scale processes through parameterization during the downscaling process. We shall address this topic later in this Chapter.

3) The biosphere is incorporated in GCMs via activities by humans, animals, plants, etc. which affect the *biomass,* especially the CO_2 budget and vegetation cover, and hence modify the energy, momentum and hydrological budgets. Again, only large-scale features are applied in GCMs. The response time of the biosphere may be in the order of days, but may extend to years or even decades.

4) *Oceans* are important because of their characteristics like salinity and their capacity to store energy for long periods. As a matter of fact, oceans have a response time that ranges from months to years for shallow layers and up to centuries for deep layers.

5) The *cryosphere* refers to the snow and ice deposits on earth. Their response time ranges from days to centuries.

Activity 2.3

1. Write down some examples of the GHGs found in the atmosphere
2. Describe changes to the land surface structure that may modify the observed weather/climate patterns.
3. Explain why the cryosphere is important in GCMs.

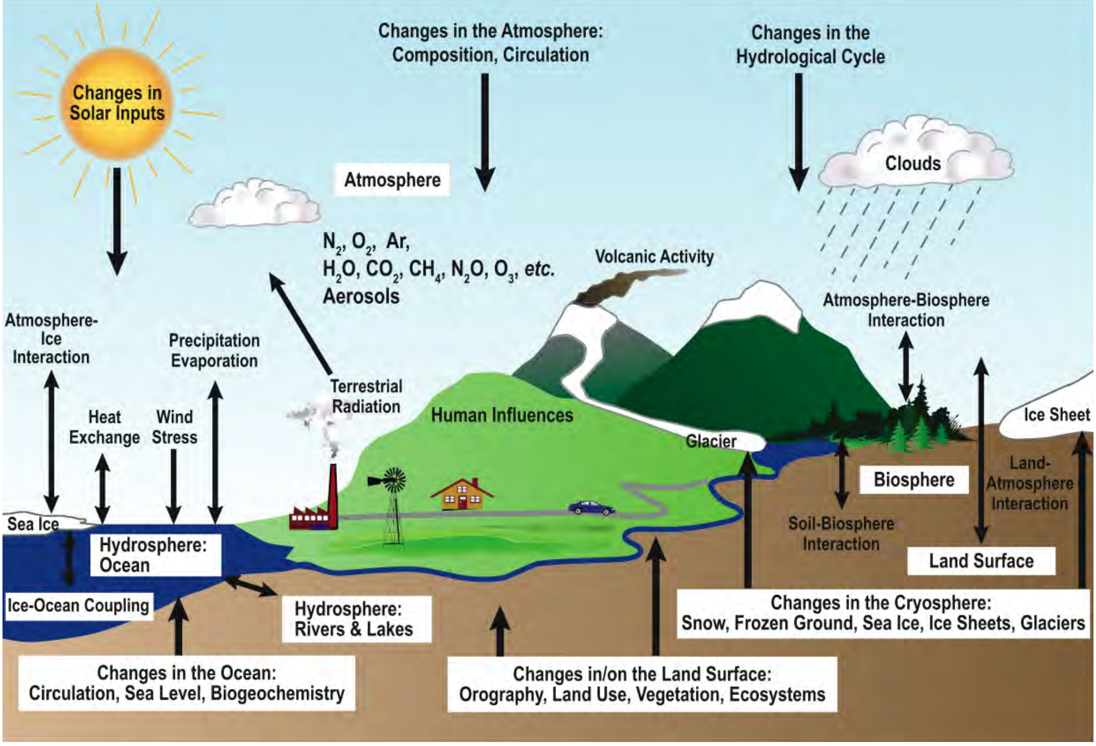

Figure 8: The Climate System. (Source: IPCC's 4th Assessment Report)

We have so far learned that to model the processes in the atmosphere we need to account for the forcing due to the atmosphere itself, but also activities on land, and processes in the biosphere, ocean and cryosphere. We shall now examine the main processes modelled in GCMs.

2.2.5 Physical Processes of the Climate System Computed in GCMs

What are the main processes computed in GCMs? GCMs incorporate three main processes:

1) The first crucial aspect in modelling is the computation of the net radiation. In calculating the net radiation, it is important to include the effects of season, albedo, cloud cover, winds, water vapour, CO_2 and Ozone (O_3) content. The technical phrase for this energy is “net radiation flux divergence”. Determination of the net radiation from short-wave and long-wave irradiance is one of the most time-consuming activities in GCMs.

2) The second very important aspect in GCMs is how different important quantities that influence the climate in the lowest part of the atmosphere (called the boundary layer) are transported through the atmosphere. These quantities are energy (in relation to sensible and latent heat), momentum (in relation to wind motion), and matter (especially relating to moisture). The transport (or flux) of these quantities in the atmosphere is erratic in nature, so we use the phrase “turbulent” fluxes. To this end, GCMs involve calculations of the turbulent exchange of heat, momentum and moisture.

3) The third very important aspect in GCMs is inclusion of processes that happen on scales that are much smaller than the grid spacing of the model, and how they interact with other scales of motion. In the previous Chapter, we noted that GCMs are coarse models and fail to capture systems on small spatial scales. We call such processes “subgrid scale” processes. To calculate such processes, we use an approximation approach which we term “parameterization”. The para-meterized subgrid scale processes and how they interact with other scales of motion include the effects of cumulus convection, boundary-layer processes, surface processes, topography and irradiative heating.

So far we have seen some of the technical aspects of GCMs. We shall now turn our attention to examples of GCMs used for climate and climate change studies. In the next section, we shall examine some of the examples of GCMs.

Activity 2.4 Group discussion

1. Discuss why we may refer to all the three processes discussed above as “subgrid-scale” processes.
2. Where would you expect subgrid-scale processes to be computed?

2.2.6 Examples of GCMs

What are CMIP5 and CORDEX? In 1995, WMO, under its World Climate Research Programme (WCRP), set up a project to compare the performance of coupled global climate models under the name Coupled Model Inter-comparison Project (CMIP). CMIP5 is the fifth phase of the project.

In 2009, the WCRP initiated the Coordinated Regional Downscaling Experiment (CORDEX) programme. This was in response to the need for a coordinated frame-work for evaluating and improving regional climate downscaling. The programme sought to produce fine-scale climate projections for identified regions worldwide. It also sought to link the climate modelling community and end users of climate information globally.

Both CORDEX and CMIP5 data are available from various sources of the Earth System Grid Federation including the Swedish Meteorological and Hydrological Institute-National Super-Computer (https://esg-dn1.nsc.liu.se/projects/esgf-liu/) and the German Climate Computing Centre (https://esgf-data.dkrz.de/projects/esgf-dkrz/).

These models are mainly applied in climate change studies. The models in CMIP5 are given in Table 2.

Table 2: Global Centres that are involved in the CMIP-5 Programme

Modelling Center	Institution
BCC	Beijing Climate Center, China Meteorological Administration
CCCma	Canadian Centre for Climate Modelling and Analysis
CMCC	Centro Euro-Mediterraneo per I Cambiamenti Climatici
CNRM-CERFACS	Centre National de Recherches Meteorologiques / Centre Europeen de Recherche et Formation Avancees en Calcul Scientifique
COLA and NCEP	Center for Ocean-Land-Atmosphere Studies and National Centers for Environmental Prediction
CSIRO-BOM	Commonwealth Scientific and Industrial Research Organisation, Australia, and Bureau of Meteorology, Australia
CSIRO-QCCCE	Commonwealth Scientific and Industrial Research Organisation in collaboration with the Queensland Climate Change Centre of Excellence
EC-EARTH	EC-EARTH Consortium
FIO	The First Institute of Oceanography, SOA, China
GCESS	College of Global Change and Earth System Science, Beijing Normal University
INM	Institute for Numerical Mathematics
IPSL	Institut Pierre-Simon Laplace
LASG-CESS	Institute of Atmospheric Physics, Chinese Academy of Sciences; and Tsinghua University
LASG-IAP	LASG, Institute of Atmospheric Physics, Chinese Academy of Sciences
MIROC	Atmosphere and Ocean Research Institute (University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
MOHC	Met Office Hadley Centre (additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)
MPI-M	Max Planck Institute for Meteorology
MRI	Meteorological Research Institute
NASA GISS	NASA Goddard Institute for Space Studies
NASA GMAO	NASA Global Modeling and Assimilation Office
NCAR	National Center for Atmospheric Research
NCC	Norwegian Climate Centre
NICAM	Nonhydrostatic Icosahedral Atmospheric Model Group
NIMR/KMA	National Institute of Meteorological Research/Korea Meteorological Administration
NOAA GFDL	Geophysical Fluid Dynamics Laboratory
NSF-DOE-NCAR	National Science Foundation, Department of Energy, National Center for Atmospheric Research

Original source from: http://cmip-pcmdi.llnl.gov/cmip5/availability.html

Activity 2.5

1. Why are some GCMs termed as non-hydrostatic?
2. Explain why it would be advantageous for a dynamical climate modelling centre to have an ocean component GCM (i.e. OGCM) in addition to land-atmosphere component GCM (i.e. AGCM) to be “coupled”?

2.2.7 Other Climate Change Models

Before we leave our discourse on model design and selection, let us review some of the other tools that may be used for projecting future climates.

The Providing Regional Climates for Impacts Studies Model

The Providing Regional Climates for Impacts Studies (PRECIS) is a regional climate modelling system, whose aim is to allow developing countries, or groups of developing countries to generate their own national scenarios of climate change for use in impacts studies. Based on the third generation of the Hadley Centre’s regional climate model, PRECIS is not just flexible in design, but it also has a user-friendly data processing and visualization interface, which allow for its application anywhere on earth. PRECIS is driven by boundary conditions from the Hadley Centre GCMs forced by four Special Report on Emission Scenarios (SRES) cases. PRECIS may be used to provide regional details in finer-resolution (50 km and 25 km) regional climate model projections than what is obtained by GCM outputs. Detailed information on PRECIS may be obtained from http://www.metoffice.gov.uk/precis/.

Model for the Assessment of Greenhouse Gas Induced Climate Change and SCENario GENerator

MAGICC-SCENGEN stands for the Model for the Assessment of Greenhouse Gas Induced Climate Change and SCENario GENerator. This is a coupled, user-friendly, and interactive suite of software that allows for investigation of future climate change and its uncertainties at regional and global levels. The MAGICC software performs calculations of mean global level taking cognizance of the upwelling-diffusion and energy-balance model used by IPCC. SCENGEN applies the results from MAGICC alongside the outputs from the CMIP archive of AOGCMs to yield spatially detailed information on future changes in temperature, precipitation and mean sea-level pressure, changes in their variability, and a range of other statistics. More detailed information on the model is available at http://www.cgd.ucar.edu/cas/wigley/magicc/.

Statistical Downscaling Model

The Statistical DownScaling Model (SDSM) is a tool for assessing local climate change impacts at a location using sophisticated statistical downscaling techniques for decision support. SDSM enables the speedy advancement of numerous, low-cost, single-site scenarios of daily surface weather variables under current and future regional climate forcing. The software also performs additional jobs of pre-screening predictor variables, calibrating models, testing basic diagnostics, analysing and plotting climate data. More information on the model may be obtained from the site http://co-public.lboro.ac.uk/cocwd/SDSM/software.html.

The LARS-WG Weather Generator

The Long Ashton Research Station Weather Generator (LARS-WG 6.0) is a stochastic weather generator. It is a computationally inexpensive downscaling tool to generate local scale climate scenarios founded on global or regional climate models for impact valuations of climate change. The current version of LARS-WG integrates climate projections from a number of global climate models from the CMIP5 ensemble used in the Fifth Assessment Report of the IPCC. LARS-WG has been applied in assorted climates worldwide. The use of the tool in a research project requires a license; and it may not be used for commercial applications. More detailed information may be obtained at https://sites.google.com/view/lars-wg/.

Activity 2.6

1. Visit the sites of the climate modelling tools discussed above, and write short notes about each of the models.
2. Explain the fundamental differences among these climate modelling tools.
3. Why is it important that the climate modelling tools discussed above be linked to GCMs?

2.3 Downscaling Global Climate Models

2.3.1 The Rationale for Downscaling Climate Information

Most processes that control local climates such as the effect of terrain undulations, vegetation and hydrological systems are not explicitly included in GCMs because GCMs have coarse resolution. The horizontal grid sizes in GCMs are typically hundreds of kilometres (from 1°, or 111 km to 5° or 555 km at the equator). Studies over regions and formulation of policy require that climate information be availed at a higher resolution (less than 50 km in the horizontal). To include information from GCMs at local scales, we need to downscale the GCMs. The downscaling exercise takes the known information at large scales and uses it to simulate the climate at local scales (Figure 9).

Important to Note

Downscaling is the process of relating large-scale climatic features from GCM outputs to smaller spatial scales to be relevant in various applications.

What is the difference between numerical and statistical downscaling?

Numerical downscaling, which is also known as *dynamical downscaling*, involves the use of a regional climate model (RCM) or mesoscale model “nested” within the GCM, or using the GCM outputs as initial and spatial boundary conditions in the RCM or mesoscale model. *Empirical-statistical downscaling* on the other hand employs applying statistical relationships between the large-scale climatic state and local variations derived from historical data records of the GCM outputs. Let us commence by discussing dynamical downscaling.

2.3.2 Dynamical Downscaling of GCMs

The percentage of either land or water in a grid box is called the *land-water mask (or land-sea mask).* The land-water mask is the simplest ancillary file in a model that tells us whether a particular grid square is land or sea. This file is created by interpolating (usually a high-resolution) dataset of the fractional sea or land cover to the required model grid. If the total proportion of land is over 50%, then the point is classified as a land point, otherwise it is taken as a sea point.

In dynamical downscaling, we run climate models that have a resolution that is higher than that of GCMs, but on a regional sub-domain, using a RCM. In this exercise, we use lower resolution data from a climate model or together with observed data. A RCM is analogous to a GCM but with higher horizontal resolution and supplementary regional information to enable the model to represent the local landscape, and possibly local atmospheric processes better. Regional models use physical principles to try to reproduce local climates. Practically, the main benefit of RCMs is their capacity to model atmospheric procedures and land cover changes more explicitly. The downside of these models is that they use more computing resources.

Figure 9 shows the land-water mask of a region on the earth’s surface with each box (grid resolution) representing an area of about 500 km by 500 km (or approximately 5° by 5°), with red indicating land surfaces and white representing water bodies.

Activity 2.7

Consider the region shown in Figure 9. Try to recognize the region indicated in the figure on a world map.

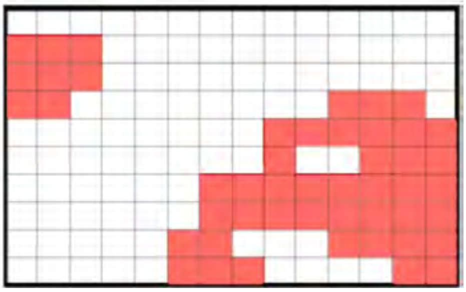

Figure 9: The land-water mask (land is red and water white) showing a region on the earth's surface with a grid spacing of 500 km by 500 km. Courtesy: Prof Delyang Chen, Goteborg's University, Sweden

From Figure 9, because of the low resolution, it is difficult to know which area on the earth's surface is represented by the schema. Now let us suppose that we increase the number of grid boxes (or grid resolution) in our region by decreasing the grid spacing. This is shown in Figure 10. We see immediately the high cost of increasing the resolution to improve the representation of our area, which we can now clearly identify in the final figure at a resolution of 110 km. We not only have to deal with many more grid points, but we also have to deal with many more mechanisms in an explicit way! Figure 11 shows the application of downscaling from a GCM with a resolution of 100 to 300 km using RCMs with resolutions of 50 km and 15 km, down to a hydrological model of 1 km!

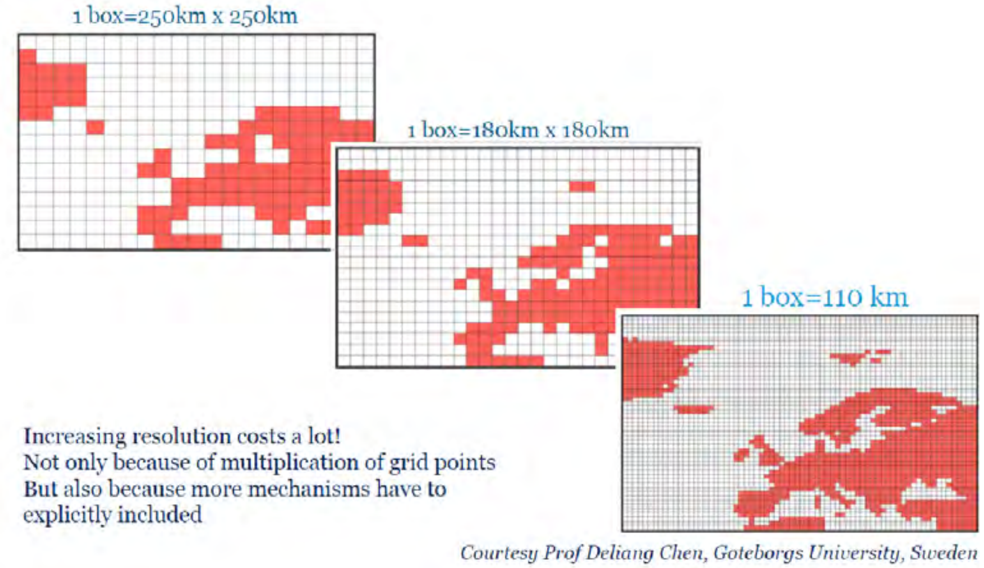

Figure 10: Illustration of how increasing the grid resolution improves the representation of the earth's surface.

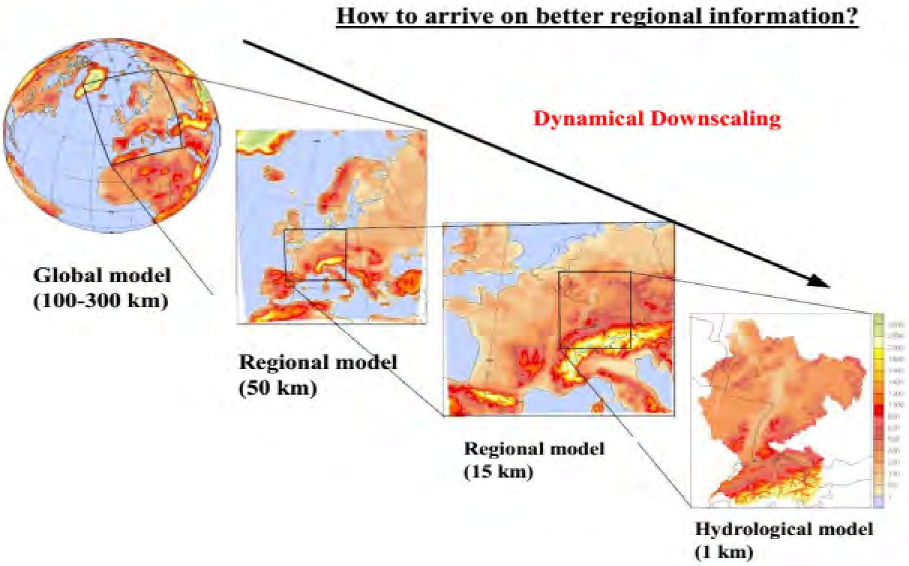

Figure 11: Illustration of how increasing the grid resolution improves the representation of the earth's surface. Courtesy: Klein et al. 2005

We shall now turn our attention to statistical downscaling.

2.3.3 Statistical Downscaling

In statistical downscaling, the process employs two steps. The first step entails developing a statistical relationship between the climate variables at a locality and large-scale fields. For instance, we may relate the surface air temperature or precipitation and large-scale predictors like pressure fields. The second step entails applying such a relationship to the output of global climate model experiments to simulate local climate characteristics in the future. Unlike RCMs that produce downscaled projections at spatial scales of tens of kilometres, statistical downscaling can provide climate information at a station. Upon establishing and validating the statistical relationship, future large-scale atmospheric conditions predicted by GCMs are used to project future climate characteristics at a location.

Let us illustrate statistical downscaling in a simple example. Suppose that observed historical data from models (which we shall call X) and observations (which we shall call Y) shows that Y depends on X, and we may determine Y given X by a regression tool. We can then develop a simple relationship of the form:

$$Y = a + bX$$

If such a relationship exists and if *a* and *b* are known constant values; and further, if we can estimate the future value of X, we can conveniently determine the future value of Y. We call the above equation a *bivariate linear regression model*.

Now suppose that in the above example the atmospheric variable X has been predicted using the dynamical model (GCM) and we wish to statistically predict the atmospheric variable Y at a point (e.g. at a station) using this established relation, we can in this way relate the historical GCM outputs (e.g. model precipitation, sea surface temperature, etc.) and the historical observed values (of say precipitation). We call this process "statistical downscaling".

If our regression equation is such that one value depends on more than one other value, we call this a multivariate linear regression model. Such a model would have the form given below:

$$Y = a_0 + a_1X_1 + a_2X_2 + \cdots + a_nX_n$$

In the above equation, in which a_1, a_2, a_3, …, a_n are constants and X_1, X_2, X_3, …, X_n are predictors of Y (which we refer to as the predictand).

Despite the efficiency of statistical downscaling, its relatively lower computational demands, and a diverse range of techniques, the method makes certain assumptions that are not always true. To begin with, statistical downscaling presupposes that there exists a stationary statistical relationship between the predictor and predictand. Put differently, by stationarity, we mean that the relationship does not vary with time and that the variation is stable. Secondly, statistical downscaling assumes that the large-scale variables represent the climate system. With this assumption, the technique presupposes that the signal of the changing climate is within the predictor. Thirdly, the technique assumes that there exists a robust relationship between what is predicting (the predictor) and what is predicted (the predictand). This entails evaluation to determine whether or not the assumption has validity. Finally, statistical downscaling assumes that the GCMs are perfect in simulating the predictors which is of course untrue.

Activity 2.8

1. State the major limitations of downscaling GCMs statistically.
2. What are the challenges of dynamical downscaling?

Before we can use model outputs in various applications we need to determine how effective the model outputs are.

2.4 Model Quality Assessment

What causes uncertainties in model outputs? Dynamical modelling involves using science and technology to predict the future state of the atmosphere which in this compendium we shall refer to as *forecasting*. Climate forecasting is attained by collecting the quantitative climate data on the current and past state of the atmosphere at a given place and using known laws to project how the atmosphere is likely to evolve. By comparing the predicted values (F) with the observed values (O) we can gauge how good the forecasting system is.

2.4.1 Basic Model Evaluation Terminology

GCM forecasts are more often than not biased in various ways, which requires calibrating the output (denoted by the letter F) against the observed data (denoted by the letter O). For example, a model may be consistently too dry or too wet; too warm or too cold. To make these corrections, we use model verification and validation techniques.

Model verification is the process of assessing the quality of a prediction (i.e. model outputs or forecasts). Verification involves comparing the prediction and what actually occurred. It can be qualitative, where our interest is in how good the output looks, or quantitative which entails assessing how accurate the forecast is.

Although the words *verification* and *validation* are sometimes used interchangeably, the two terms are different. When we assess how well the model replicates the reality (observations), we are doing verification; if our interest is to establish how good the model is for the intended purpose, we are doing validation. Verification is concerned with the extent to which the model output agrees with the observations, but validation is about the extent to which the model is good enough for use by stakeholders. In verification, we ask the question “Is this model working well (compared to observations)”? In validation, we wish to know “Is this the right model (for the user’s needs)”? Put differently, verification focuses on the model, but validation focuses on the user.

2.4.2 Model Output Verification

Model outputs should be accompanied by readily available information on the quality of the forecasts. This information may be obtained by using data from forecast archives and observations through a set of diagnostics. Forecast verification is necessary because of several factors. First, we wish to monitor the quality of the forecast. In other words, we wish to discover if the accuracy of forecasts is dependable and improving over time. Secondly, we wish to improve forecast quality and discover what went wrong. Lastly, we may wish to compare the quality of different forecast models and establish how one forecast system is better than another system.

A forecasting system (model) is good if it fulfils three things: first, it should be consistent. A model that consistently underestimates or overestimates the forecasted quantity is essentially a good model. Secondly, the model should have quality. By quality, we mean that the model output should be reliable. A prediction of “heavy rain” or “freezing temperature” has low quality if no rain falls or the temperatures are high. But the prediction may have value if the prediction for heavy rain or low temperature is accurate in the neighbourhood, and people take precautions. Thirdly, the prediction should have value: the output should be useful economically, in decision making, for planning. A forecast of “no rain” or “high temperature” in a desert has quality (i.e. it is accurate) but has little value (as it is expected).

2.4.3 Model Verification Metrics

Qualitative assessment of the forecast involves using the eyeball method. In this approach, we visually examine the forecast and observations side by side. Data is presented as time series and maps and human judgment used to discern the forecast errors. The advantage of this method is that it is useful for few forecasts. The disadvantages are that the method is time consuming, and that it is prone to individual, subjective biases of interpretation.

What are scatter diagrams? Another way of determining the quality of a forecast by a model is by using scatter plots. Scatter plots involve plotting the forecast values against the observed values. Scatter plots answer the question: how well did the forecast values correspond to the observed values? In an accurate forecast, points lie on or near the diagonal. We can also plot the difference between forecasts and observations (i.e. forecast minus observation) against forecasts, or forecasts minus observations against observations, and determine how close or far the values depart from the zero line, telling us where the model over-forecasts or under-forecasts. For this written work, we shall use the following arbitrary data (Table 3). Figures 12 and 13 show the associated scatter diagrams.

Table 3: Temporal variation of temperature compared with the observed data

Day	1	2	3	4	5	6	7	8	9	10
Forecast, F_i	5	10	9	15	22	13	17	17	19	23
Observed, O_i	-1	8	12	13	18	10	16	19	23	24

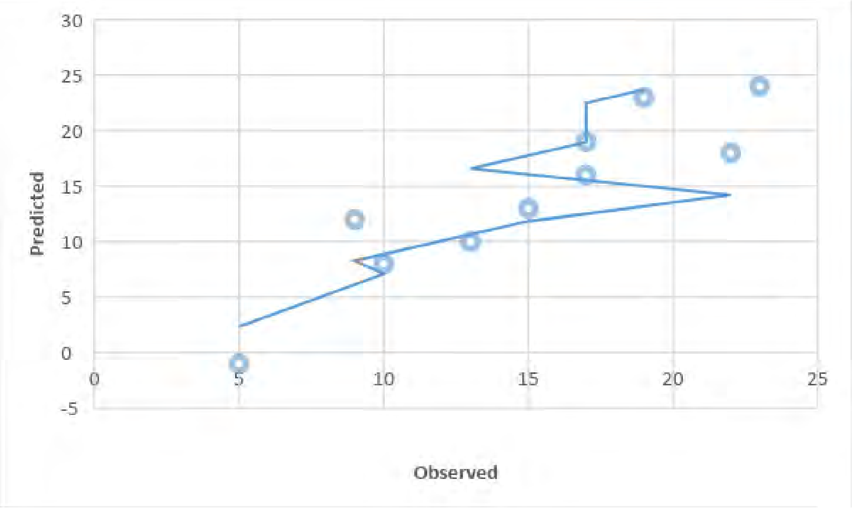

Figure 12: Scatter plots showing forecast data against observed data

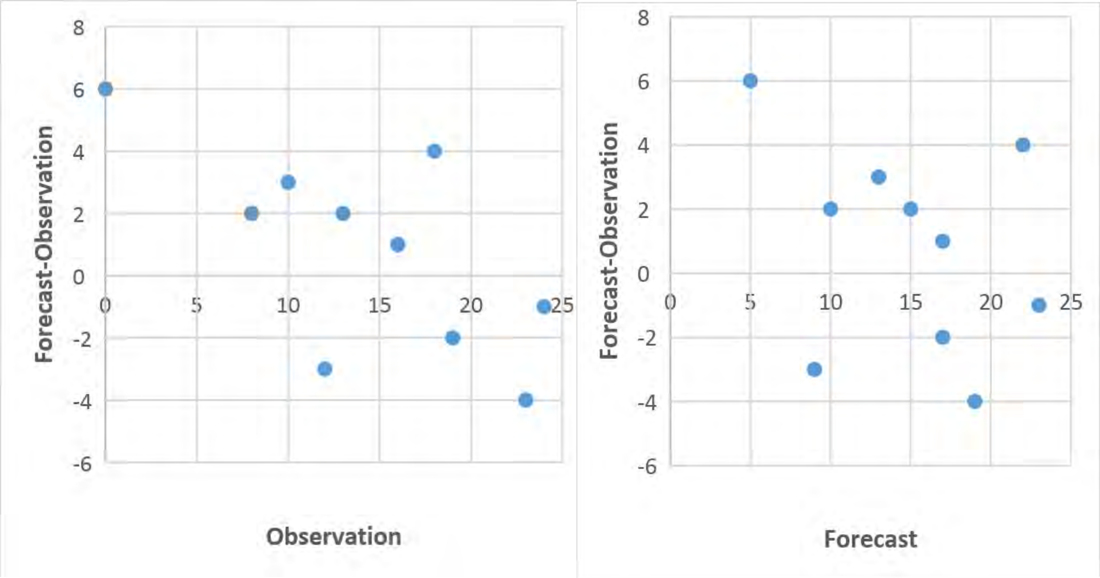

Figure 13: Illustration of forecast verification using scatter plots

What is bias? Having examined qualitative measures, let us now turn our attention to quantitative metrics. To determine how well a mean forecast corresponds to a mean observation we use *bias*. Bias answers the question**:** how does the average magnitude of the forecast compare to the average magnitude of the observed data? We have two types of bias: multiplicative bias and additive bias. Multiplicative bias is defined as the ratio of the mean of forecast quantities to the mean of the observed quantities, given by the equation below, in which F stands for forecasts and O represents observations for N corresponding values:

$$Bias = \frac{1}{N}\sum_{1}^{N} F_i \Big/ \frac{1}{N}\sum_{1}^{N} O_i$$

Additive bias given by the expression:

$$Bias = \frac{1}{N}\sum_{1}^{N}\left(F_i - O_i\right)$$

The multiplicative bias ranges from negative infinity (-∞, under-forecasting) to positive infinity (+∞, over-forecasting) with the perfect score being one (1). The additive bias ranges from -∞ (under-forecasting) to +∞ (over-forecasting), with a perfect score of zero (0). This score is also called the mean error. Both the multiplicative and additive biases have the advantage of being simple and familiar. Their disadvantage is that the scores do not indicate the direction of the deviations. Using the data provided, the multiplicative and additive biases are respectively 1.06 and 0.8, indicating borderline over-forecasting.

What is Correlation? We now turn our focus to measures of linear association. Association measures how good the linear correlation between the forecasts and observations, r is ranging from -1 to +1, with 1 being the perfect score. The correlation coefficient answers the question: how well did the forecast values correspond to the observed values. The advantage is that it is a good measure of linear association or phase error. Visually, r measures how close the points of a scatter plot are to a straight line. The disadvantage is that it is sensitive to outliers and that it does not take forecast bias into account: it is possible for a forecast with large errors to still have a good correlation coefficient. The Pearson's correlation coefficient r is given by the formula below:

$$r = \frac{\sum_{i=1}^{N}\left(F_i - \overline{F}\right)\left(O_i - \overline{O}\right)}{\sqrt{\sum_{i=1}^{N}\left(F_i - \overline{F}\right)^2}\sqrt{\sum_{i=1}^{N}\left(O_i - \overline{O}\right)^2}}$$

The square of r, called the coefficient of determination is a measure of how much variance is correctly explained. Using our data, the correlation coefficient has a value of 91.4%, and the coefficient of determination is 83.5%!

Anomaly correlation (AC) answers the question: how well did the forecast anomalies correspond to the observed anomalies? It ranges from -1 to +1 with the perfect score being 1 (or 100%). AC measures the correspondence or phase difference between the forecast and observations, deducting the climatological mean at each point C rather than the sample mean values. Like for Pearson's correlation, the anomaly correlation has the disadvantage that it is not sensitive to forecast bias. It should be noted that high AC does not guarantee accurate forecasts. The formula for AC is as given below. Assuming that our climatological mean is 14°C, we get a value of 90.4%

$$AC = \frac{\sum_{i=1}^{N}\left(F_i - C\right)\left(O_i - C\right)}{\sqrt{\sum_{i=1}^{N}\left(F_i - C\right)^2}\sqrt{\sum_{i=1}^{N}\left(O_i - C\right)^2}}$$

What is mean error? Let us now turn to measures of accuracy. Accuracy relates to how large or small the error is between the forecast and the observations. The mean error (ME) answers the question: what is the average forecast error? It ranges from -∞ to +∞, with a perfect score of 0. The ME is also called the additive bias. Its advantage is that it is simple and familiar. Its disadvantage is that it does not measure the magnitude of the errors. Moreover, it does not measure the corre-spondence between forecasts and observations, i.e. it is possible to get a perfect score for a bad forecast if there are compensating errors. The ME is given by the formula below. In our example, the mean error is 0.8°C

$$ME = \frac{1}{N}\sum_{1}^{N}\left(F_i - O_i\right)$$

What is mean absolute error? The mean absolute error (MAE) answers the question: what is the average magnitude of the forecast errors? MAE ranges from 0 to +∞, with the perfect score being 0. MAE has the advantage of being simple and familiar. Its disadvantage is that it does not indicate the direction of the deviations. MAE is given by the formula below. Using our arbitrary data, the MAE is 2.8°C.

$$MAE = \frac{1}{N}\sum_{1}^{N}\left|F_i - O_i\right|$$

What is root mean square error? The root mean square error (RMSE) answers the question: what is the weighted average magnitude of the forecast errors? It ranges from 0 to +∞, with a perfect score being 0. Its advantage is that it is simple, familiar, and measures the "average" error, weighted according to the square of the error; it puts greater influence on large errors than smaller errors.

It has the disadvantage that it does not indicate the direction of the deviations; it may encourage conservative forecasting. The RMSE is given by the formula below. Using our arbitrary data, it would have the value of 3.2°C.

$$RMSE = \sqrt{\frac{1}{N}\sum_{1}^{N}(F_i - O_i)^2}$$

What is skill? Skill answers the question how accurate is a forecast over some reference forecast? Skill has to do with how the accuracy of one model compares with that of other models or an observed standard. Hence, the measures of accuracy above may be used to determine the skill of the forecast. The most skilful model would have the lowest bias, highest correlation, least error, and highest score.

What is reliability? Reliability is a measure that tells us how well the forecast values agree with the observed values on average. It is the same as bias when all forecasts are considered together.

What is sharpness? Sharpness has to do with how well the forecasting system predicts extreme values. If a model is good at predicting floods or droughts, or heat waves and cold waves, it has high sharpness.

Having studied **2.9**

Refer to the data in Table 4. Using these, compute the verification indices below.

1. Plot the scatter diagrams (forecast against the observed values) for the two models. Try to determine the better model in predicting temperature.
2. For the two models, plot also the scatter diagrams of forecast minus actual values against (i) the observed (ii) forecast. Which model has a higher bias, and in which direction?
3. Compute the correlation coefficient and the coefficient of determination, and compare your values to the scatter diagram in (1) above.
4. Compute the multiplicative bias and the additive bias for the two models. Compare your results to your inference made following the diagrams in (2) above.
5. Compute the mean absolute error and the root mean square errors for the two models.
6. Which model has better skill?
7. Which model is more reliable?
8. Which model simulates the observed temperature over the period better?
9. Correct the bias for each model using both the computed multiplicative bias index and the additive bias index. Hence, plot the new model values against the observed values.

Table 4: Model and Observed Temperature (°C)

Year	**1971**	**1972**	**1973**	**1974**	**1975**	**1976**	**1977**	**1978**	**1979**	**1980**
Model 1	25.8	25.9	25.8	25.7	25.9	25.8	25.8	25.8	25.8	26.1
Model 2	26.2	25.5	26.9	25.1	26.1	25.1	26.6	25.4	26.8	25.8
Actual	25.7	26.0	26.4	25.6	25.6	25.6	26.1	25.9	26.3	26.3
Year	**1981**	**1982**	**1983**	**1984**	**1985**	**1986**	**1987**	**1988**	**1989**	**1990**
Model 1	26.1	25.8	25.7	26.3	26.2	25.8	26.3	26.4	26.6	26.6
Model 2	26.6	25.4	26.7	25.6	26.7	25.5	27.3	25.8	26.7	26.0
Actual	26.1	25.9	26.2	26.1	26.2	26.0	26.8	26.3	26.2	26.5
Year	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**
Model 1	26.4	25.8	25.5	26.1	26.1	25.9	25.8	26.3	26.8	26.3
Model 2	26.6	25.4	26.6	25.5	26.9	25.7	26.5	26.3	26.8	25.9
Actual	26.1	25.9	26.1	26.0	26.4	26.2	26.0	26.8	26.3	26.4

2.5 Applications of Climate Models

Climate data is required by both individuals and corporations. Climate models including GCMs are applicable to many sectors.

Activity 2.10

Demonstrate the various applications of climate models.

There are some applications of climate modelling, ocean surface modelling, air quality modelling, tropical cyclone forecasting, wildfire forecasting, as well as climate effects on health, food security, agriculture, forestry, water management, etc. Let us give a brief outline on some representative applications of climate model data by scientists, individuals and companies.

2.5.1 Climate Modelling

GCMs mimic either the average circulation of the atmosphere of the planet (or AGCM), the ocean (OGCM), or both (AOGCMs). Coupled AOGCMs are used in modelling the influence or forcing of oceans on the state of the climate of the whole globe (e.g. that arising from El Niño and La Nina events), thereby enabling us to better understand the climate. The models are equally beneficial in projecting climate change by integrating a range of man-made scenarios due to the release of chemicals into the atmosphere to gauge how a heightened greenhouse effect would adjust the climate of the earth with timescales ranging from decades to centuries, when run for long periods, in the order of decades at low horizontal resolution, disregarding smaller-scale interactions.

2.5.2 Ocean Surface Modelling

The creation, interchange (propagation), grouping (shoaling), and refraction of waves, and the transfer of energy among the waves, including their dissipation, depends on the transfer of energy between the surface wind blowing over the ocean surface and the upper layers of the ocean. The information about the surface wind comes from GCMs.

2.5.3 Air Quality Modelling

In air quality modelling, scientists attempt to predict the conveyance, dispersion, alteration and deposition of air pollutants and guesstimate if and when the concentrations of pollutants will get to hazardous levels with respect to public health. Urban air quality models involve the application of very high resolution models.

2.5.4 Tropical Cyclone Forecasting

The development, intensity and movement of tropical cyclones may be done either by applying statistical techniques developed from the climatology of the storms (which we refer to as climatology and persistence, or CliPer, models), dynamical methods, or a combination of both of these methods.

2.5.5 Wildfire Forecasting Sector

Since wild fires depend on the conditions of the atmosphere, including elements like wind direction and speed which determine the direction the fire is advected (i.e. carried without a change in its internal properties), to the humidity (which affects gas fuels), and temperature and its variation with height, which affects the stability of the atmosphere, the use of climate models in wildfire forecasting is very important. Wildfires may also affect the flow of air by changing the local advection patterns, thereby introducing a feedback loop between the atmosphere and the fire. These processes and feedbacks may be simulated by using climate models.

2.5.6 Farming and Agriculture Sector

The economic success of the farmer dependents on the planting, irrigating and harvesting of crops at the right time. It is also important that the farmer chooses the right crops for the local climate. With this understanding, the interest of farmers in weather and climate is taken for granted. Farmers depend on short-range weather forecasts on temperature, precipitation, and soil moisture levels to decide on taking actions like when to irrigate the crop. Evidently, longer-term projections of climate over a region in the form of precipitation, temperature, and soil moisture, allows farmers to decide on the type of crops to grow in the future and which technologies to invest in.

2.5.7 Urban Planning

Extreme temperature has been associated with casualties in many western countries. In the United States for instance, heat waves claim more lives in a year than floods, lightning, tornadoes, and hurricanes put together. Authorities are therefore rightly concerned about possibilities of projected increases in the frequency, duration, and intensity of heat waves associated with climate change. With this information, city officials may issue warnings to the public, and institute energy-saving programmes, and set up cooling centres in communities. By and by, authorities may develop strategies to adapt to high temperature and plan for long-term infrastructure investments to protect the economic and health interests of their people. Such actions may be in the form of zoning certain areas to mandate tree planting activities for shade, investing in power-grid infrastructure, and organizing programmes to increase the efficient use of energy.

2.5.8 Water Management and the Energy Sector

In order to make decisions on how much water to conserve, both in the short- and long-term, river managers may use climate projections of temperature, precipitation, and snow pack to plan for and adapt to future changes in water volumes in rivers, such as in the case of increased runoff in the spring or reduced flow in the summer. Climate projections would allow for better planning and assist to inform on investments in infrastructure.

2.5.9 Insurance Industry Sector

The rates in the insurance industry depend on the expected occurrence of events like weather and climate-related disasters in the form of droughts, floods and high winds. The rates are calculated using historical climate data of these weather events to develop models on risk for diverse regions and operations such as in farming, construction or transportation. Notwithstanding, weather and climate-related damage has surged in recent years. These losses by insurance companies have thrown light on the possibility that the changing climate has made past events to no longer be a reliable guide on what would happen in the future. High quality regional climate projections of sea level, temperature, precipitation, wind, and extreme events are necessary for more accurate reflection of the changes in risks.

2.5.10 National Security Sector

National security planning and decision making makes use of climate information, including forecasts over a broad range of timescales. This has necessitated the need to incorporate climate change into the management of military operations, missions, and facilities. Sea-level rise of a few feet would affect naval facilities and assets. Navies therefore need climate model outputs for information related to higher maritime activities, water and resource scarcity, and the bearing of sea level upsurge on military installations. Evidently, regional climate models with high spatial resolution providing information on decadal timescales are crucial to inform decision making.

Activity 2.11: Group discussion

Discuss the importance of climate modelling for the forestry sector.

2.6 Summary

Dynamical climate models are mathematical descriptions of the climate system of the earth represented using horizontal grid points but with multiple vertical levels. GCMs are coarse models, describe the general behaviour of the atmosphere, and simulate seasonal and annual cycles. GCMs consider the atmosphere, the biosphere, the land surface, the ocean, and the cryosphere components. The mathematical aspects that receive special attention in dynamical modelling are radiation; turbulent exchange of heat, momentum and moisture; and subgrid-scale processes. Outputs from large-scale models may be related to smaller spatial scales by using statistical methods or by nesting limited area models into the GCMs and solving the equations numerically. Downscaling lets us derive information at a localized level from larger scale forecasts and projections. It involves adding local information like topography, hydrology, forest cover, and land characteristics. It therefore requires specific resources and expertise. In using multivariate regression, we should be wary of the problems of *multicollinearity* and *multiplicity*. Forecast verification is done to monitor, compare, and improve forecast quality. The benefit of forecast verification to scientists is to correct inherent errors; to administrators, verification is done to demonstrate value in their funding, and to the common person, the benefit of verification is to demonstrate that forecasts have value. Forecasts are good if they are consistent over time, have quality, and have value. Verification is done for continuous variables using various measures. Forecast outputs are sometimes corrected to remove biases of various models. Dynamical model outputs may be applied in nearly all aspects of the socio-economic fabric of nations.

2.7 Self-Assessment

Activity: Self-assessment Questions

1. Describe the general properties of GCMs.
2. Describe how constituents of the climate system are incorporated in GCMs.
3. Discuss the main processes computed in GCMs.
4. List five examples of GCMs.
5. Explain why downscaling of GCM outputs is needful.
6. Distinguish between numerical and statistical downscaling.
7. Explain some statistical techniques employed for downscaling GCM outputs.
8. Explain some dynamical techniques employed for downscaling GCM outputs.
9. Distinguish between linear and non-linear bivariate regression, and between linear and non-linear multivariate regression.
10. Distinguish between multicollinearity and multiplicity. Explain how these problems may be addressed in statistical modelling and prediction.
11. Why is it necessary to verify forecast products?
12. State three attributes of a good forecast.
13. Explain the differences between accuracy, reliability, sharpness and skill of a forecast.
14. Discuss forecast verification metrics used in dynamical model outputs.
15. Discuss some of the socio-economic uses of climate model information.

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Chapter 3: Climate Scenario Development and Projections

General Objective:

By the end of the chapter, the learner should be able to demonstrate increased understanding of the climate change scenarios and the possible effects of changes in climate to forestry and related sectors.

Scope:

- Basic concepts in climate scenario development
- Climate projections over Africa

3.1 Chapter overview

Recent reports indicate appreciable shifts in the observed global climate, and scientists now have a better understanding of the possible causes of these changes. Evidence of these shifts exists in the form of historical records from tree rings, fossils and ice cores. Recent changes in the climate system have been attributed to both natural agents, like solar irradiative forcing, continental drift, variations in earth's orbit, and anthropogenic agents, involving changes induced by human activities.

Expected Learning Outcomes

By the end of the chapter, the learner should be able to:

1. Explain basic concepts in climate scenario development and projections.
2. Define the terminologies, categories and methodologies used in climate scenario development.
3. Explain the design and history of climate scenario development.
4. Describe the projected trends in some climate elements over Africa.
5. Evaluate the implications of projected regional and local climate on forestry and related sectors.

In the next section, we discuss the basic concepts used in climate change scenario development and climate projections.

3.2 Basic Concepts in Climate Scenario Development and Projections

What are some of the basics in the development of climate scenarios and climate projections? In this section, we shall discuss the climate scenario development process and climate projections.

3.2.1 Climate Scenarios and Climate Projections

The observed climate is best understood by defining a period of historical data that climatologists refer to as the *baseline*. A baseline period has a duration of usually thirty years with continuous climate data that acts as a reference for future and past climates.

Climate projection is founded on how the climate system responds to forcing from anthropogenic activities like aerosols and GHGs in the atmosphere. These forcings are incorporated into climate models to give meaningful information, including the difference between current and future climate. Forcing is defined using “scenarios”.

A scenario is a setting or picture of what is likely to happen in the future, assuming that certain conditions hold. A scenario is therefore not a prediction. Scenarios help us to appreciate the possible consequences of the phenomena being investigated. Climate scenarios are illustrations of the likely future climate premised on possible effects of anthropogenic (human-induced) activities, like the effects of the release of pollutants into the atmosphere. Scenarios may be premised on higher future temperature, higher or lower precipitation.

Climate scenarios are applicable for studies on impact of climate change and strategies for assessing adaptation to these changes.

The scenarios act as awareness-raising tools and for decision-making. When used in analysing the vulnerability and adaptation to climate change, scenarios have to provide information on a scale in space and time that is compatible with the scale on which the impacts occur, like a watershed or farm; some analyses may be on monthly or daily, or even sub-daily timescales.

Activity 3.1

- Determine the adequacy of climate projections for studies on the impact of climate change on any sector.
- How would the choice of the baseline climate affect the assessment of climate change over a region?

3.2.2 Climate Scenario Development Process

What does the climate scenario development process entail?

Designing Climate Scenarios

The type of climate scenario required depends upon various factors. For instance, we may need to know the nature of the influence, the specific geographical location, and the necessity. We may also need to know the needed climate variables, like rainfall, temperature, humidity and wind, and their timescales as well as the needed space scales, e.g. whether regional or local application of future climate. How we define forestry would influence how the forestry sector would be affected.

In designing climate scenarios, we first specify the baseline climate which serves as a reference for future changes in climate and for assessing the impacts. The climate baseline also becomes the basis for making projections and characterising critical features of the current climate regime, like seasonality in the climate parameters, the extreme events, and the local weather phenomena.

The second step in designing climate scenarios involves determining how we may derive the changes and natural variability of climate through enhanced GHG effects from a variety of data sources, using various methods and tools. The third step is the development of climate scenarios. The final step comprises detailed documentation that describes the variety of techniques, tools and data sources used, including their limitations. Such documentation provides guidance to scientists on the interpretation of the scenario and their intended usages. A good scenario should be consistent with global projections, be physically credible, be applicable in impact assessments, be representative, and be easy to access, interpret and apply in assessing impacts.

Climate Scenario Development Process

Climate change scenarios have been used by IPCC to assess the possible changes in climate. The IPCC scenario A (SA90) set developed in 1990 sought to examine four emission pathways: three policy scenarios and a future with “business as usual” (BaU). In 1992, the IS92 IPCC scenario set was developed to consider the consequences of technology, population, and growth (termed as “unknowns”) in several cases of “BaU” futures regarding projected GHGs and short-term emissions of pollutants on economic growth and energy usage, and associations of economic convergence between developing and developed countries. The SRES involved many modelling teams guided by narratives or “storylines” of the possible future. At the time of writing this compendium, the scenarios adopted by the IPCC AR5 are termed as Representative Concentration Pathways (RCPs). RCPs were designed to meet the needs of both users and developers of climate scenarios.

There are two main approaches to climate scenario development: parallel and sequential approaches. The sequential approach (Figure 14) entails building emission scenarios from socio-economic future, approximating irradiative forcing and concentrations coming from emissions, and using climate models to project the future climate which is then used for impact assessment. The downside of this process is the amount of time it takes from the development of emission scenarios to their use in modelling before finally availing the results for assessment studies.

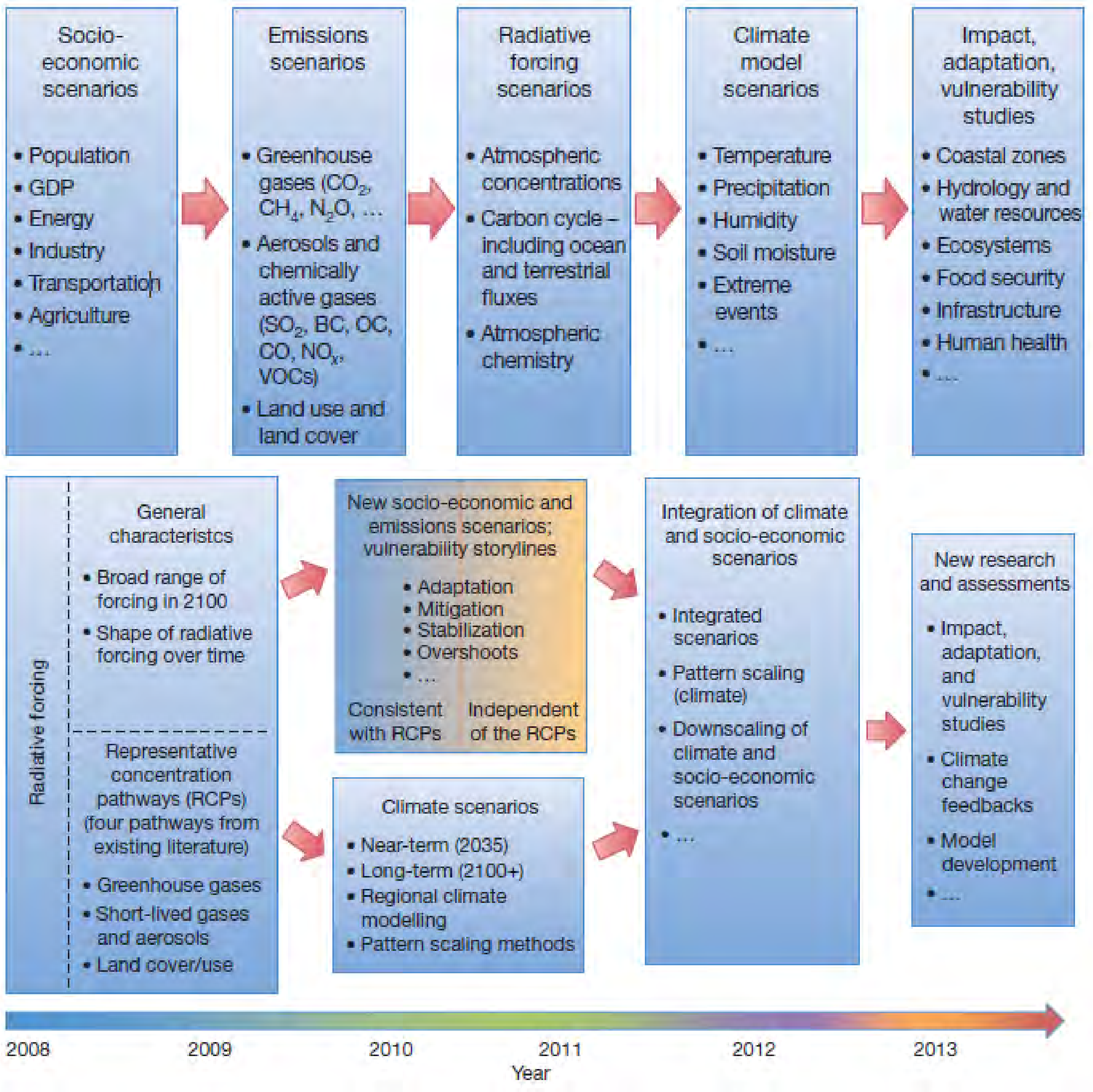

Figure 15: A flow chart showing parallel method

In the parallel approach, socioeconomic and climate scenarios are generated in parallel (Figure 15), which makes it possible to implement policy changes.

3.2.3 Special Report on Emission Scenarios and Representative Concentration Pathways

What is the difference between SRES and RCP? SRES was founded upon four categories or families: A1, A2, B1 and B2. The scenarios suppose irreversible changes and cover a variety of "future" possibilities like economic, demographic and technological changes. Out of the four families, 40 SRES scenarios were developed. To illustrate this, an intensive fossil fuel intensive scenario was represented by A1FI, while a balanced energy sources was represented by A1B, and A1T represented a mainly non-fossil fuel scenario.

RCP are named depending on their level of forcing by the year 2100. There are four categories, viz. RCP 2.6 Wm^{-2}, RCP 4.5 Wm^{-2}, RCP 6.0 Wm^{-2} and RCP 8.5 Wm^{-2}. RCPs are chosen to represent the span of the irradiative forcing. Its estimates in RCPs do not include the direct impacts of the forcing of mineral dust or land use (albedo), nor do they represent specific technological, political or economic changes or futures pathways or climate policy action or inaction. Table 5 shows RCPs.

Table 5: Representative Concentration Pathways

Reference	Meaning	Period	Basis
Historical	Historical data	1951-2004	Hindcast (i.e. simulated using present day model configurations)
RCP26	Representative Concentration Pathways 2.6, 4.5, 6.0 and 8.5	2005-2100	IPCC projected global temperature increase by an average of 1°C by 2046-2065, then 1°C during 2081-2100
RCP45			IPCC projected global temperature increase by an average of 1.4°C by 2046-2065, then 1.8°C during 2081-2100
RCP60			IPCC projected global temperature increase by an average of 1.3°C by 2046-2065, then 2.2°C during 2081-2100
RCP85			IPCC projected global temperature increase by an average of 2°C by 2046-2065, then 3.7°C during 2081-2100

There are three main categories of scenarios. Incremental scenarios are those based on the incremental technique. In this method, specific climatic elements are increased progressively through research or absolute values, e.g. maximum or minimum temperature may be increased by 1, 4, 6 degrees. However, incremental scenarios are limited in the sense that the increments are not necessarily realistic as well as the expected changes in climate.

Analogue scenarios are whereby recorded climate regimes that would be similar in future to that of a given location are identified. Such scenarios may be spatial, in which the current climate in certain regions or locations resembles the anticipated climate in a different region, or temporal analogues which suppose "BaU" scenarios in which human systems are expected to maintain similar activities in future as they do currently. Temporal analogues may be based on instrumental data or palaeo-climatic data.

The third category of scenarios are those based on outputs from climate models (GCMS). GCMs can provide reliable, measurable outputs of projected climate at large scales. Models have the capability of replicating the observed features of past and current climates; temperature being replicated better than precipitation. GCMs have consistently shown increasing temperature due to the rising levels of GHGs in the atmosphere and are used in generating scenarios of climate for impact assessment through downscaling to regional, national and even to catchment levels.

Activity 3.2

- State the major differences between SRES and RCPs
- Discuss specific climate elements whose change will influence forestry, or a related sector.

Practical exercise

Objective: To demonstrate climate change using a suite of climate change models.

Requirements: Install the MAGICC-SCENGEN software in your computer. The Magicc-Scegen model may be downloaded from the website: http://www.magicc.org/download. Useful information about the package is available at http://www.cgd.ucar.edu/cas/wigley/magicc/.

Group Discussion

a) Illustrate temperature projections over your region of interest or country under different choices of SRES.

b) Illustrate temperature projections over your region of interest or country under different choices of SRES.

3.3 Climate Projections over Africa

What is the status of climate projections over Africa? Weather and climate are essential for vegetation growth and determine the location, organization and eco-system of forests. Future climate projections will influence the distribution of forests.

3.3.1 Projected Trends in Temperature, Rainfall and Sea-level

According to the latest IPCC assessment report, the temperatures in Africa, especially in the Arid and Semi-Arid Lands (ASALs), is likely to increase more than over other parts of the world by the middle to the late 21st Century, and this is under both high and low emissions. According to these projections, the average temperatures will escalate in excess of 2°C under high emission scenarios. In fact, the projected alterations in temperature will be more pronounced over the southern and northern parts of Africa compared to the central parts. Low emissions are associated with average temperatures below 2°C by the mid-century going towards the end of the century; higher emissions would result in higher maximum and minimum projected temperatures over North Africa. Over W Africa, particularly in the Sahel, projections indicate a possible rise in temperatures in the order of 3°C to 6°C towards the year 2100. Over equatorial E Africa, projections based on medium to high emission scenarios point towards minimum and maximum temperatures increasing with more warmer days than the baseline. The south-western and north-western areas of S Africa are projected to have rapid warming.

Unlike for temperature, projections of future rainfall are highly uncertain in most parts of the African continent. In the case of low emission scenarios, many parts of Africa fail to show any significant change in the annual average rainfall. In contrast, high emission scenarios seem to indicate the likelihood of decreased annual rainfall in S Africa in the middle to the end of the century. Rainfall is likely to increase over eastern and C Africa. Over N Africa on the other hand, the region is very likely to receive less rainfall with both low and high emissions towards the end of the 21st century, indicating seasonal to annual warming and drying under high emissions. Although the observed rainfall over E Africa shows a decreasing trend, global projections indicate a possibility of the region experiencing fewer droughts and wetter and more intense wet October-December and March-May seasons. Drier conditions and shorter rainfall seasons are expected over E Africa by mid of the 21st century. Global projections that the south-western parts of S Africa could be drier.

Projections of low and high emission scenarios show the likelihood of a rise of sea level as we move towards the end of the century. This possibility would be associated with enhanced risk to ecology, livelihood and culture of people near coastal areas.

Warmer sea surface temperatures, extreme weather and an upsurge in sea level would be expected to damage coral reefs and could affect the ecology of the susceptible mangrove trees which act as protective layer against storms, and which effect would be aggravated by cutting down of the trees, increased coastal erosion, and weather events that are of the extreme kind. This would be especially hazardous in the event of inundation of low-lying coastal areas and intrusion of salt water. Figures 16, 17 and 18 illustrate climate change models over parts of Africa.

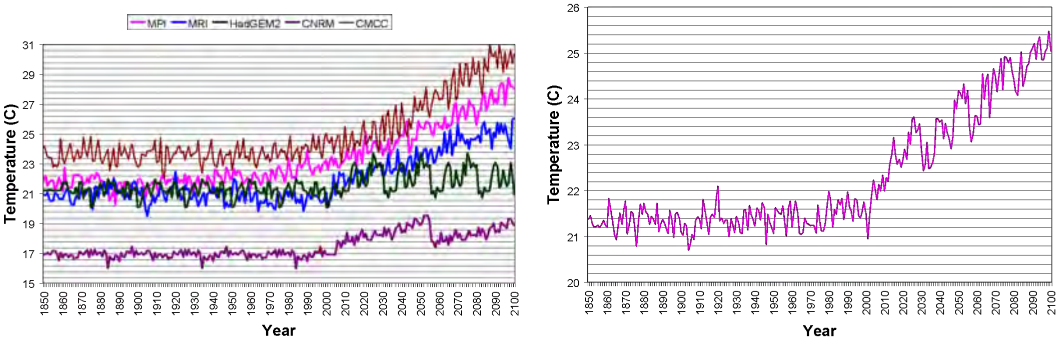

Figure 16: Historical and projected (RCP 4.5 scenario) temperature variation at Kitale (Kenya). From five GCMs (MPI, MRI, HadGEM2, CNRM, CMCC CMIP5 Models) from 1850 to 2100 (left) and a multi-model ensemble (right)

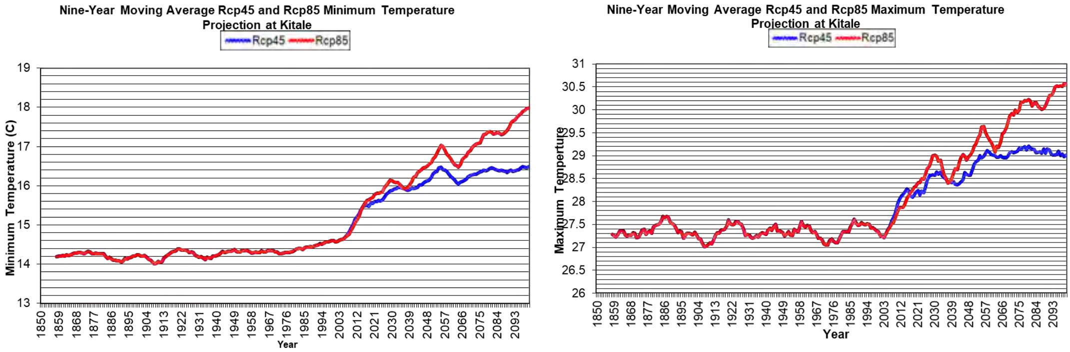

Figure 17: Nine-year moving average of minimum and maximum temperature at Kitale, Kenya for the RCP 4.5 and RCP 8.5

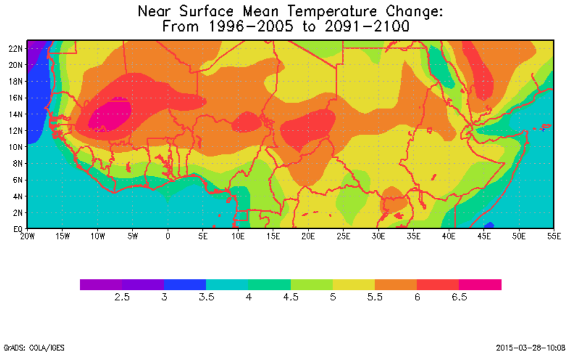

Figure 18: Projected mean temperature rise in the RCP4.5 (2040-2049) and RCP8.5 (2091-2100) vis-à-vis 1996-2005 using the MPI CMIP5 Model

3.3.2 Implication of Projected Climate on Forestry

What are the implications of the projected climate change on forestry and related sectors? Available evidence seems to indicate that climate variability and change influence the forest ecosystems and biodiversity in many parts of Africa. Some of these manifest in decline in the variety of plant and animal species, upsurge in the risk of wildfires, scarcity in forest products and modifications in forest ecology. It goes without saying that the changes in forest ecosystems are likely to impact negatively on communities that derive their livelihood from the various forest ecosystems, including variability or reduced availability of products and services from them.

Let us first focus on the possible loss of biodiversity and disappearance of wildlife habitats. Global patterns of forest vegetation forms envisage up to one-tenth to one-half of biome cover to be vulnerable to future climate towards the end of the century. Model simulations indicate species losses due to climate change of up to or even exceeding 50%! Climate variation is anticipated to markedly modify the distribution of some animal and plant populations on the continent. It is possible that biomes that are sensitive to precipitation during the growing season may be affected adversely while hostile species may adapt to alterations in optimal environments. Changes in ecosystem functions and composition may further impact the diversity of various species.

Secondly, we have disturbances to forest systems. Climate is known to expressively affect pests and diseases, wildfires, and other regimes and invasive species. These disturbances influence the distribution, frequency, spatial extent and intensity of forests. Fundamental changes in average climate will mostly influence the future shocks on forests.

The third aspect has to do with limited availability of forest products. The proper usage of forest products and good forest management are among strategies to mitigate the amounts of CO_2 levels in the atmosphere. Forest management entails the optimisation of practices that increase forest growth (i.e. carbon management), planting trees, and limiting or prohibiting the destruction of existing forests.

The final aspect we consider is shifts in forest ecosystems. It is expected that the changes in rainfall and temperature will strongly affect adapted and natural forests. Biogeographical models have indicated a poleward shift in potential vegetation, which may result in an expansion of forest in areas with optimal conditions, and a decline in forest area where the conditions are no longer favourable.

Activity 3.4

Analyse the implications of future climate on forestry in your country or region.

Practical exercise

Using appropriate computer and electronic devises, display future temperature variation in time.

Requirements: (1) Computer (preferably with internet link); (2) GrADS software installed, (3) Excel software installed; (4) RCP 4.5 and 8.5 scenarios, (5) CoRDEx data (temperature and rainfall for at least two models in the suite of models).

Exercise questions

a) Display of future temperature variation in time.

b) Display of future rainfall variation in time.

c) Display of future temperature change in space for RCP 4.5.

d) Display of future temperature change in space for RCP 8.5.

e) Display of future rainfall change in space for RCP 4.5.

f) Display of future rainfall change in space for RCP 8.5.

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Chapter 4: Application of Climate Change Modelling in Forestry and Related Sectors

General Objective:

By the end of the chapter, the learner should be able to under-stand the application of climate change modelling in forestry and related sectors.

Scope:

- ✓ Forest ecosystems
- ✓ Allometric equations for Carbon sequestration and projection.
- ✓ Reference emission levels.
- ✓ Modelling forest ecosystems.

4.1 Chapter Overview

Climate models have the ability of providing reliable measurable outputs of the projected climate which is especially true at large scales. More recently, there have been significant improvements in the principles upon which these models are founded, which has enabled more reliable replication of the observed features of present and past climate especially for temperature but also for precipitation.

Expected Learning Outcomes

By the end of the chapter, the learner should be able to:

1. Define the basic terms and concepts in forest ecosystem management.
2. Describe the use of allometric equations in Carbon estimation and projection.
3. Explain the need and process of establishing reference emission levels.
4. Describe the tools for modelling forest ecosystems.

To enhance the learner's understanding on the application of climate change modelling in forestry and related sectors, we shall commence our discourse by discussing the basic concepts used in forest ecosystems studies.

4.2 Forest Ecosystems

In this section we shall consider the importance of forests and the management of forest ecosystems.

What are forests? A forest is defined as a dense collection of trees and other forms of vegetation covering a relatively big area. Alternatively, we may define a forest as a complex ecosystem made up of trees. According to the FAO, forests are portions of land with a real coverage exceeding half a hectare with tree canopies covering more than 10%, and reaching a minimum of five metres at maturity. Natural forests are those that mainly consist of indigenous trees, while plantation forests are those established through seeding or planting through reforestation or afforestation.

What is the importance of forests? Forests cushion the earth's surface and support the existence of a diversity of forms of life. Forests create a distinctive environment of trees that determine the nature of flora and fauna living within it, including numerous microorganisms. In providing shade, trees cool the air on hot days, clean the environment, act as absorbers of sound, and preserve the warmth during the night. In doing these things, trees play an important role as an indispensable part of the environment.

Forests have other equally important roles. The tree canopy assists in ameliorating the force of falling rain water. In doing this, the trees prevent soil erosion. Moreover, decaying foliage on the ground limits runoff thereby enabling the seepage of water into the ground. The roots of trees hold the soil in place. Further, decaying foliage and dead plants help in the formation of humus. Trees not only release large quantities of oxygen, they also sequester large volumes of CO_2 from the atmosphere.

Forestry is the science or art of planting, growing, cultivating, exploiting and renewing trees in forests. It encompasses the practice, science and art of managing forest stands and forest resources sustainably for the benefit of man. Foresters have the necessary expertise in caring for not just trees but all resources within forests. These resources include trees, people, animals, insects, diseases, soils, and water.

What is forest ecosystem management? An ecosystem is a collection of all living things in an area including all animals, plants, and organisms. The living things interact among each other and with their environment. Ecosystems are the basis of the biosphere and thus dictate the health of the whole climate system. Forest ecosystems are lands covered by trees and consisting of biologically associated plants, animals, and microbes.

Forest ecosystem management (FEM) is the management of the exploitation of forests by people and the interaction of people with forests. FEM addresses the usage, preservation, control and administration of forests, taking cognizance of the complexity, high integration, and multiplicity of the biophysical system that determines the optimal values for disturbance of the ecosystem, while preserving the systems' resistance, its specific characteristics, and its eco-friendly services. FEM is characterized primarily by sound ecological models and understanding, complexity and connectedness, dynamicity of ecosystems, context and scale, humans as ecosystem components, sustainability, adaptability and accountability.

Activity 4.1

- ✓ How are forests defined in your country or region?
- ✓ What measures are employed to conserve forest ecosystems in your country or region?

4.3 Allometric Equations for Carbon Estimation and Projections

In forest management, we require reliable regression equations relating field measurements of tree variables such as height and diameter to complex variables like biomass with which we may be able to estimate properties of a forest ecosystem. We achieve this by employing allometric equations.

What are allometric equations? Allometry refers to the study of the process or differential rates of growth and development of parts of the body of a living thing. It is the interconnection between physical attributes like morphology, physiology and ecology, and biological scaling. Tree allometry refers to relating parts of a tree that are easy to measure and other parts that are not easy to measure, such as the size of a tree and its growth, using statistical equations. The equations have the capacity to calculate the biomass of trees and to deduce the outcomes to the entire stand or forest. Tree allometric equations apply regression techniques between the height and diameter of a tree to the volume or biomass, allowing the stand or forest biomass to be quantified without the need to destroy the tree (i.e. destructive sampling), take it to the laboratory, drying the pieces, and weighing the pieces in an environmentally friendly way. Allometric modelling cost-effectively calculates biomass and Carbon stock of forest stands by applying simple and easily measurable tree variables during forest inventory. However, the initial development of the allometric equations is costly and laborious, requiring destructive sampling of forest/biomass; it is also time-consuming and cumbersome for very big trees.

What is biomass? The word biomass refers to the total mass of a living or dead thing or all the dead or living things within a habitat. Put differently, biomass is the total mass of dead or living organic matter or dry weight of a plant or tree. The change of biomass density (i.e. vegetation biomass per unit area) is used as a measure of Carbon sequestration. When we refer to trees, we talk of wood density. Wood density is dependent upon the species of the tree and its location. Estimates of biomass are useful in determining the amount of Carbon content in forests using suitable conversion factors. For example,

$$C = 0.47B$$

$$CO_2 = 3.66C$$

In the above equations, B stands for biomass, C is Carbon and CO_2 is Carbon dioxide. The basic IPCC formulae for the GHG emission assessment accounts for activity records based on national or international statistics and emission dynamics.

Allometric equations are mathematical formulae developed using datasets from many different parts of the globe. For this reason, their accuracy is uncertain when applied to field data from other regions. The uncertainty arises from differences in certain factors of the tropical forests like the species composition, the wood density of the species, the maximum height, the height-diameter relationships, and the size of the crown. It follows therefore that the total “above-ground” biomass and its relationship with measurable variables may also differ.

How do we develop allometric equations? Before developing allometric equations, we need datasets on wood density which may be determined by measuring the diameter of the trees, counting their number, determining the climate of the area where the trees are harvested, the nature of the forest, and other geo-referenced information. The data may be obtained through destructive sampling in which we sample, fell and chop up some trees of the desired species to obtain a representative dataset. The chopped up components that may include the stem, branches, and twigs, are weighed, and the sub-samples of the components put together for drying, weighing, and other laboratory analyses to determine the wood density. Non-destructive sampling involves collecting core samples from selected sample trees, and then determining the wood density.

To develop species-specific biomass equations, we begin by checking for a relationship between the biomass and the independent variables. After this, we select the best models. Since the relationships are normally not linear, we make use of logarithmic relationships. Using natural logarithms, we transform the best regression equation models into a linear logarithmic form. We can employ forward, backward or stepwise variable selection methods to identify the optimum number of independent parameters for the equation. At the same time, we also fit the models based on biomass components and the total above-ground biomass. We may use graphical or statistical approaches to compare the performance of the developed models.

Activity 4.2

✓ What sampling techniques are employed in your country or region to collect field data?

✓ Give examples of allometric equations used in your country or region.

Practical exercise

Develop allometric equations and apply them in Carbon emission**.**

Requirements: Dataset biomass_data.csv, inventory_data.csv, R_Script and R software.

Group Discussion

✓ Determine the R and important R package used in modelling forest biomass/Carbon.

✓ Evaluate the relationship between biomass and independent variables.

✓ How is selection of model expressions for fitting biomass/Carbon models done?

Perform model fitting procedures; and select the best biomass/Carbon models.

4.4 Reference Emission Levels

The reference emission level is a point of reference upon which we may quantify the reductions in the past, present and future projected emissions at national and regional scales.

What is the need to establish reference emission levels? In order to manage the amount of Carbon from terrestrial ecosystems, we may employ sustainable AFOLU practices by controlling the cutting down of trees and building new Carbon from these terrestrial ecosystems, e.g. by planting more trees. In this regard, we need to establish reference “sequestration and emission” levels at the outset as the baselines against which we measure success. The Kyoto protocol set up certain rules for setting reference levels through its “clean development mechanism”. Techniques for establishing sequestration and emission levels for terrestrial Carbon have been developed in spite of inadequate rules.

How can we estimate emission and removal of GHGs from the atmosphere? Three tiers or levels were established by the IPCC based on the accuracy of the data. For the first layer (Tier 1), the emission factors as prescribed by the IPCC are based on activity datasets at large (global) spatial scales. The second layer (Tier 2) employs the datasets as in Tier 1, but incorporate emission factors from individual countries or specific regions particularly for the most crucial groupings of land use. The third layer (Tier 3) employs inventories of complex procedural methodologies that may include measurements and models at finer resolution to deal with recurrent situations over a given time at national and sub-national levels.

What are the policy implications in reference to establishing emission scenarios? Setting up reference emission levels requires policy considerations. The first policy consideration has to do with scale. In spite of international agreements, reference levels require to be set up at national and subnational levels to provide checks and balances on terrestrial Carbon as one of the solutions to climate change.

The second policy has to do with the scope. The control of terrestrial Carbon in developing countries for climate change adaptation and mitigation may require incentives on land management and terrestrial Carbon activities while setting up reference emission levels. Options include Reducing Emissions from Deforestation (RED), Reducing Emissions from Deforestation and Degradation (REDD), Reducing Emissions from Deforestation and Degradation plus afforestation, poverty alleviation, biodiversity conservation, and improved forest governance (REDD+), Reducing Emissions from Deforestation and Degradation plus afforestation, poverty alleviation, biodiversity conservation, and improved forest governance and emissions from other land conversions (REDD++); and AFOLU.

Another policy would involve the conceptual approach. Four main conceptual approaches have been adopted in establishing reference emissions. These are the status quo, BaU, pragmatic, and negotiated approaches. The status quo approach advocates for ways that only provide motivations to countries which have a history of emissions. The BaU approach proposes awarding contributors in systems with improved performance as relates to a future without incentives. The pragmatic approach is premised on the assumption that it is impossible to define a BaU reference level, and proposes the use of past data as the only dataset. The negotiated approach supposes that an essential or meaningful outcome will result from an agreement among several countries to have reference levels and proposes that reference levels be determined by different approaches.

Yet, another policy addresses the major drivers and constraints considered. The approach is founded upon the fact that to establish a reference emission under the BaU method, we require to evaluate the Carbon risk of emission with respect to the drivers and constraints on emissions from changes in land use. The drivers and constraints must be tackled by addressing the legal basis, biophysical considerations, and economic aspects.

Finally, in this discourse, we need to address the issue of feasibility and other considerations. To this end, different countries need to agree on reference emissions in respect of the ease of accessing data.

Activity 4.3

✓ Why is there a need to set reference emission levels in your country or region?

✓ What are some of the approaches and tools that would be useful to set a reference emissions level in your country or region?

4.5 Modelling Forest Ecosystems

Humankind has adversely influenced the amount of forest cover on most continents on earth. This has led to a significant reduction in the land area covered by forests as well as the distribution of tree species. To determine the extent to which these changes have happened, we may make use of ecological modelling techniques, but this should be backed by observational and biological realisation needs. Needless to say, observational data from the field has been a major constraint.

Why do we need ecosystem models? Environmental changes and the impact of these changes may be investigated through applying forest ecosystem models. In this regard, we use historical data as well as projected information. The major limitation of ecological model development is unavailability of past and current information for various reasons, mainly lack of monetary resources and dedication, which have made it difficult to undertake continuous long term measurements.

A second limitation is in the methodology applied. The techniques which are mainly experimental are often not openly applicable to complex environmental change. These models are used merely as research tools to increase our knowledge, as management tools to assist in making policy decisions, and as educational tools to aid us to understand the earth system. Before choosing a model, one should first establish that the approach is sensible and the models are not just reliable, but also applicable, and the data are available for model validation.

Finally, we shall now turn our attention to the tools used in modelling forest ecosystem. The purpose of ecosystem models is to compute, describe and reproduce a variety of ecosystem processes that are influenced, not just by the changing ecosystem characteristics, but also by the changes in management and other effects caused by the environment.

What are growth and yield models? The first tool we consider is the growth and yield models. The wellbeing of a forest may be assessed by analysing regular forest records. Needless to say, extrapolation of forest growth is required for planning. Inventories of forests are used together with predictions from forest growth models in order to give the information needed to make viable decisions at national, regional or global levels. Conventionally, yield tables have been relied upon but with certain conditions. Cohorts with similar characteristics such as age and type of a species make these cohorts distinguishable from other forest stands. The average stage growth is defined by assessing a specified quality of the location. The main focus of growth and yield models is to compute the future growth of a stand to prevent excess felling and misuse of forested resources. More recently, forest management has shifted to forested lands whose trees have a big difference in age. The focus on uneven-aged forests has led to improved yield tables and have in some cases been substituted by growth models. This concept is due to the fact that uneven-aged species would add or maintain existing soil fertility, enhance the variety of plants and animals, and make the forest stand more resilient. This has led to the development of growth models that run at a specific tree level with the merit being the non-dependence on individual ages, mixture or stand treatment since mortality and growth of individual tree stands is defined.

What are succession models? Succession or gap models are those that define the mortality and reproduction growth of trees. The models are based on the assumption that older trees will die leading to gaps in the forests that we would expect to be filled by new trees that will grow. The growth potential of specific species is computed in a similar way to that for location-specific types used in management. This is followed by derivation of response functions. Even though the simulation of tree growth is done, the main purpose of gap models is to give a description of periodic vegetation distribution, in addition to focusing on the description and insight into the already prevailing patterns based on the period over which changes in the vegetation occur.

What are biogeochemical-mechanistic models? Biogeochemical or mechanistic or process models provide a description of the transformation, circulation, and accumulation of energy within and through a forest ecosystem. The main aim of these models is to study the relationship between plants and their immediate environments. Biogeochemical-mechanistic models are preferred in grasping and detecting the characteristics of ecosystems. Compared to succession models, biogeochemical-mechanistic models integrate a mechanistic component comprising of interrelationship of plants and their immediate environment; these models are intended to show the response of plants to changes in environmental conditions. Biogeochemical-mechanistic models run on daily to monthly time scales, stand level and require meteorological data as an input; their strength is the ability to describe the Carbon cycle. *What are hybrid models?* In hybrid models, we combine the concepts utilized in the growth and yield, succession and biogeochemical-mechanistic models. By so doing, we advance the application of the models as modelling is now fully integrated into ecosystem research. Hence, the limitation of each model is reduced and the different models make it possible for modellers to design a new model for empirical based information. In this kind of setting, it is always necessary to assess the sensitivity of the models and examine any missing gap in terms of our knowledge of ecosystem processes before embarking on data collection.

Activity 4.4

- ✓ Explain why you would require an ecosystem model in your country or region.
- ✓ Describe the different models that can be used to study climate change and forest ecosystems.

Practical exercise: Assess the effects of climate change on forest ecosystem

1.Getting started with LANDIS-II

The goal of the exercise is to familiarize users with the basics of running the model and the resources available to learn about the model. The user will learn how to run the model, understand the purpose of the scenario and log files, and gain experience debugging input files.

Requirements: LANDIS-II v6.0 installed with the Age-only succession, base fire, base wind, base harvest, and output max species Ageextensions. **Note:** For this exercise, you will only be manipulating text files.

Group Discussion

a) When would you use:
  - DisturbancesRandomOrder?
  - RandomNumberSeed?

b) What determines the overall computation time of a simulation?
  - How important are resolution and extent?
  - What other factors come into play?
  - If the computation time is overly long, what steps might you take to speed up simulation?

c) Strange behaviours and model failure to run are not uncommon, particularly for free and open-source software, if you encountered an unexpected problem, where should you seek assistance?
  - What information should you report and to whom?

d) Read through the species file (notepad) and use the Model User Guide (and your own knowledge) to answer these questions:
  - Is the model limited to these species parameters?
  - Do species names require quotes?

e) Read through the ecoregion file (notepad) and use the Model User Guide and your own knowledge to answer these questions:

  - Are we limited to these ecoregion parameters?

  - How would you write an entry for pavement? Open water?

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