CHAPTER 6: THE UNIFIED MODEL: HISTORICAL INTRODUCTION, BASIC NUMERICAL CONCEPT AND APPLICATIONS

6.1: Introduction

The purpose of this chapter is to present an overview of the history of the Unified Model, basis of its design and numerical formulation, as well as its common use or application. Although the model is used as a turnkey system in this study, understanding of those areas are essential for the user in order to recognise any mandatory requirement or major limitations related to any of its components or schemes. In addition, of course, knowledge of its peculiarities should give some advantage to the user during the course of employing the model for this area of study.

6.2: The History of the Unified Model

6.2.1: Background

The use of numerical modelling systems in the United Kingdom Meteorological Office (UKMO) was begun more than two decades before the Unified Model was born. The UKMO started using global climate simulation models during the late 1960’s (Corby *et al.*, 1977), and has used a global numerical weather prediction model since 1982 (Gadd, 1985). By the end of the 1980’s, separate numerical prediction models were used in the UKMO to sustain climate research and operational forecast capabilities. By then, the climate model incorporated a relatively sophisticated representation of physical processes, and consisted of 11 vertical layers with a global domain at 250km horizontal resolution. The operational model, with 15 vertical layers, had simpler calculations of physical processes and a different dynamical integration scheme to that of the climate model. The operational forecast model was run in two versions: a ‘coarse mesh’ global model at 150km resolution and a ‘fine mesh’ limited area model covering Europe and the North Atlantic at 75km resolution. In addition, a mesoscale model with 15km resolution had also been developed for the UK area, and this highest resolution model carried a completely distinct formulation for both physics and dynamics.

The global forecast and climate models that were implemented before the Unified Model had many similarities, for example their structure (Cullen, 1993). The two models, however, did differ, particularly in their physical formulation. It was realised that maintenance of the two separate systems was no longer practicable or justifiable.

The opportunity to develop the new unified version occurred at the time of a major computer upgrade in the UKMO (Met. Office, 1996). The CDC CYBER 205 machine used to run separately the previous global forecast and climate models was replaced with the Cray System YMP with 8 vector processors in January 1990. Although the formal Unified Model project was started in the UKMO in July 1989, the model was only introduced into operational service in October 1991 when it operated on the Cray-YMP. Since 1994, a series of improved versions of the Unified Model have been run on a newer and more powerful platform, the Cray C90.

Since it was introduced in 1991, the Unified Model has undergone version upgrades and system enhancements with some indication of new scientific features, concentrating on the atmosphere model (Met. Office, 1996). Table 6.1 lists release dates for each version and the dates at which each operational release was upgraded. Also given is a summary of some major changes to the hardware platform and significant changes that had contributed to these version upgrades.

There is one particular feature of the model that is worthy of special mention. The model has been coded with a minimum of machine specific routines, essential feature required to loosen the dependency on a particular hardware platform (Met. Office, 1996). Hence, the model configuration, originally developed on supercomputer platforms, is now readily portable to other systems such as workstations (making it possible to use in this study).

6.2.2: The unified consideration

The Unified Model is so called because of its capability to combine and standardise the three modes: Operational Numerical Weather Prediction modelling; Climate Modelling; and Ocean Modelling. The three modelling modes share a single general-purpose code forming a modular structure to allow easy enhancements to, and interchange between, models. This modular formulation is also applicable to a wide range of temporal and spatial scales that allow it to be used for both numerical weather prediction and climate modelling as well as a variety of related research activities.

The design of the unified system supports flexible model use and can be run depending on the purposes required by a user. The model can be run in a number of different configurations, with the three main ones being “atmosphere only”, “ocean only”, and “coupled ocean/atmosphere”. In place of, or in addition to the main models, a number of sub-models are also available, for example, a simplified model of the ocean (a slab model) and models to simulate the motion of sea ice.

The unified formulation of the model also supports both the global domain of a GCM and a nested-limited-area domain of the regional and mesoscale model. The model is designed to run at any horizontal resolution reasonable for a hydrostatic model, from coarse climate resolution with just tens of grid-points in each latitude/longitude direction of the globe to a high resolution limited-area model with grid-lengths down to 5km (0.05 degrees), provided sensible parameters are chosen (Met.Office, 1996).

6.3: Numerical Formulations

A general discussion of the basic model numerical formulations is given in Appendix B to present the important concept of the fundamental physical principles and their mathematical expression. Specific details, then, will be given for the Unified Model used in this study.

6.3.1: The Unified Model prediction schemes

In modelling practice, the governing dynamic, thermodynamic and conservation equations are actually mapped on to the spherical geometry of the Earth, rather than the Cartesian (x,y,z) coordinates. Then, a reduced set of primitive equations is obtained by assuming a shallow atmosphere where the height scale of the motion is small compared with its horizontal-length scale, an acceptable approximation for horizontal scales upwards of tens of kilometres. The various terms in the so-called primitive equations and their predictive equations for the spherical polar coordinate system would be more complicated than those illustrated above. Their derivations or expressions can be found in the numerical weather prediction literature (see, for example, White and Bromley, 1994; White *et al.*, 1994; White and Bromley, 1995).

In common with most other atmospheric models, the Unified Model's atmospheric prediction scheme shares the same basic principles governed by the hydrostatic primitive equations as discussed above. In more detail, the equations of motion used in the Unified Model are actually a more accurate approximation to the equations of motion than were used in previous models (Cullen, 1993). The difference between the equations in the Unified Model from those normally used is that the full three-dimensional representation of the Earth's rotation is included, solving for the motion of a fluid on a rotating, almost-spherical planet. This is necessary when planetary-scale motions are considered, and the vertical component of the Coriolis force may be important in regions of strong vertical motion. The formulation, therefore, has been revised to include terms which ensure that the finite difference approximations remain accurate on planetary scales, and includes a complete representation of the Coriolis effect (White and Bromley, 1994; White *et al.*, 1994).

In the following paragraphs, a brief description will be given of the horizontal and vertical resolution and discretization and the time differencing scheme used by the Unified Model.

6.3.1.1: Horizontal resolution and discretization

The choice of the horizontal resolution in the Unified Model is arbitrary and may be varied by the user. In practice, however, the resolution is constrained by available computing power, a number of standard resolutions used for an application (either climate modelling, upper atmosphere studies, or weather forecasting) and model's status (either research or production). Table 6.2 summarises the global atmospheric configurations of the Unified Model used for production and research at the UKMO.

Table 6.2: Global atmospheric configurations of the Unified Model used for production and research at the UKMO. [From Met. Office (1996)]

Application	**Status**	**Resolution (degrees)**	**Grid (E-W x N-S)**	**Levels**
Climate Modelling	Research	5.00 x 7.50	48 x 37	19
Climate Modelling	Production	2.50 x 3.75	96 x 73	19
Middle Atmosphere	Research	2.50 x 3.75	96 x 73	42
Weather Forecasting	Production	2.25 x 0.83	288 x 217	19
Weather Forecasting	Research	0.83 x 0.56	432 x 325	30

Similar to the GCM, a limited-area model is also integrated in spherical polar coordinates. For any domain of interest in a limited-area model, however, a quasi-uniform horizontal resolution is obtained by placing the coordinate pole at a specific position away from the geographical pole. This allows a regional area to take advantage of the even grid spacing enjoyed in equatorial regions, and dispenses with the need to filter. It is sometimes referred to as an ELF grid (Equatorial Lat-lon Fine-mesh). Each limited-area model domain, therefore, is a rectangular section from "an equatorial" segment of this rotated grid. This also means that the Unified Model's limited area mode should be run after choosing a specific rotated coordinate pole in order to get the right domain of interest. For example, the operational regional model (for Europe) run by the UKMO has the coordinate pole at 30^oN, 160^oE for a grid-length of 0.44^o (equivalent to 50 km resolution). On the other hand, the UKMO mesoscale model (for United Kingdom) has the coordinate pole at 37.5°N, 177.5°E for a grid-length of 0.15° (equivalent to about 15 km resolution).

Two different techniques or schemes have been widely adopted by modellers for horizontal discretizations of a model. First is the finite-difference scheme where variables are represented in different type of grids, varying according to relative locations of key predicted variables (e.g., wind and temperature components), and according to whether the grid separation is regular (or approximately regular) in longitude or physical distance as the poles are approached. Secondly, there is a scheme using a spectral method by which predicted variables in this method generally include vorticity and divergence rather than the horizontal wind components and they are represented in terms of truncated expansions of spherical harmonics.

The Unified Model employs a finite-difference scheme (Cullen and Davies, 1991; Cullen *et al.*, 1993), using a regular latitude-longitude grid in the horizontal, with the variables arranged according to the Arakawa 'B' grid. This grid is one of the five lattice types, Arakawa 'A' through 'E', all are essentially defined from the solution to gravity-inertia wave equations, which are considered as part of the complete system of primitive equations (Mesinger and Arakawa, 1976).

6.3.1.2: Vertical resolution and discretization

The vertical structure of any model's variables is most commonly represented by values defined at a number of levels in the vertical. Since the first GCM employed by modellers, a minimum of two levels is required to describe the baroclinic growth of middle-latitude disturbances (Simmons and Bengtsson, 1984). A variety of higher vertical resolutions, however, has become common now to ensure a more accurate dynamical representation as well as to facilitate parameterization techniques.

For the usual "sigma" coordinate, pressure at a particular level is proportional to the surface pressure, and coordinate surfaces thus rise over rather than intersect mountains. Figure 6.1

illustrates the usual case in which all predicted variables are defined at the same levels for the σ-coordinate system.

As shown in Table 6.2, a different vertical resolution of the Unified Model has been used depending on applications and status. The Unified Model code is designed to allow any distribution of vertical levels (subject to computer memory restrictions). In practice, however, it is found that the performance of physical parameterization scheme is very sensitive to the distribution of levels (Cullen, 1993). Most users of the Unified Model, therefore, use the standard 19-level configuration shown in Figure 6.2.

The choice of distribution of vertical levels in a model must also consider the requirement for parameterization processes at the boundary layer. This parameterization requires that at least two or three model levels lie within the lowest kilometre of the atmosphere, and at least a similar number of stratospheric levels may be chosen to avoid distortion of trospospheric planetary-wave structures. Terrain-following coordinate surfaces are much more convenient in the lower layers of the atmosphere, while pressure coordinates are more likely to give accurate results in the upper layers (Cullen, 1993). For this reason, in the Unified Model, the bottom four levels use the terrain-following “sigma” level; the top three levels use pressure surfaces, and in between the levels use a mixture of the two. By this method, therefore, the model gradually follows the terrain less and less and becomes uniform in pressure with height.

According to Simmons and Bengtsson (1984), the vertical finite-difference schemes in common use are generally characterised by their second-order accuracy (for slowly varying distributions of levels) and by satisfying certain integral constraints in common with the continuous equations. For example, an energy and angular momentum conserving scheme has been proposed in a hybrid vertical coordinates (Simmons and Burridge, 1981) and it has been used in the Unified Model. The variable values in the vertical are defined by integrating the equations in spherical polar coordinates following the Simmons and Burridge technique.

6.3.1.3: Time differencing scheme

Schemes used in a model for time derivative terms within the primitive equations (for example, advection, gravity-inertia wave and diffusion processes) are different to each other mainly in terms of their order of accuracy in solving the equations. Every available scheme, however, is intended to ensure stability to its numerical solution.

To ensure stability in the Unified Model, the horizontal advection of primary variables uses a two-step Huen scheme with fourth-order accuracy at low wind speed, reduced to second order where the winds are strong (Cullen and Davies, 1991). In climate integrations, this reduction has to be made over full model levels to ensure conservation of mass, angular momentum and mass-weighted potential temperature and moisture.

Computational stability is maintained in global versions of the Unified Model by Fourier filtering at high latitudes, adjusted automatically according to the local wind speed. This filtering has to be used at high latitudes in the global model in order to prevent an undesirable restriction on the time-step that can be used. To ensure conservation of heat and moisture, it is necessary to filter increments to the temperature and moisture fields rather than to filter the fields themselves. This filtering is not required when a model is run with limited horizontal extent and, therefore, it is not available for a limited-area model.

The dynamical schemes as summarised above are described in detail in the Unified Model Documentation Paper No. 10 (Cullen *et al.*, 1993).

6.4: Parameterizations

The forms of the primitive equations given in Appendix B indicate clearly the relative importance of the parameterization processes (denoted by the two terms, P_x and K_x in Appendix B). Without the inclusion of the two terms, as we can see, the equations describing the conservation of momentum, energy and moisture would be different or even incomplete. Parameterization schemes are required in order to represent the effect of unresolved small-

scale processes (sub-gridscale processes) on larger, explicitly resolved scales, in terms of available model variables. As illustrated in the moisture conservation equation in Appendix B [i.e. Equation (B.4)], for example, the rate of change of moisture could not be calculated without parameterization terms in the model equations. This means that predictions of moisture depend solely on parameterization in a model since no existing model resolution can resolve this variable explicitly.

Figure 6.3 illustrate schematically the processes commonly included in atmospheric general circulation models. The wiring diagram, which shows all the interactions, indicates the complexity of adequately incorporating all those processes in a model. It must be recognised that different components of an overall parameterization in a model are highly interactive with each other, just as the corresponding processes are in the real atmosphere. To simplify discussions, however, every component is normally described in a separate scheme, despite much detail regarding interactions among the processes.

As in all current numerical models of the atmosphere, the parameterization of physical and sub-gridscale processes is an important aspect of the formulation of the Unified Model. In principle, the parameterizations are used in the same way both in the global and in the limited-area versions of the model. With reference to the schemes used by the Unified Model, each of parameterization schemes will be summarised separately in the following paragraphs.

6.4.1: Land surface model

The land surface scheme is most directly related to the field of study reported in this thesis. The basis of this scheme, therefore, has already been described with more detail in Chapter 3. As described, a computational method within this scheme is based on changes in the land-surface characteristics, by calculation of surface heat, moisture and momentum fluxes. The scheme used by the Unified Model is described in detail in Chapter 7.

6.4.2: Boundary layer

A parameterization of the boundary layer is undertaken to include surface exchanges and boundary layer turbulence. It approximates the exchange of heat, moisture and momentum among the lowest model layers and with the surface.

According to Simmons and Bengtsson (1984), boundary-layer parameterization schemes in atmospheric general circulation models may be divided into two classes. They depend on the vertical resolution of the model close to the ground in the boundary layer. If only one level lies within the boundary layer, then the so-called “bulk” parameterization scheme is used to represent the boundary layer as a whole. In the simplest of the bulk approaches, the surface fluxes are calculated from a basic surface drag law using either the wind at the lowest model level, or wind extrapolated from more than one level. In the second class of parameterization, the boundary layer structure is explicitly resolved by several levels within the lowest 2-km of the model atmosphere. In these explicit boundary-layer models, the lowest level is chosen to be within a few tens of metres of the ground, and surface fluxes are determined using either a logarithmic wind profile or, more generally, Monin-Obukhov similarity theory.

The Unified Model follows the explicit boundary layer method. In the maximum depth of ~ 2 km, depending on the position of the lowest inversion, its boundary layer occupies up to five model layers. Vertical turbulent transport of primary variables and tracers in the boundary layer depends on the local Richardson number. In calculating the transport coefficients, the presence or absence of cloud is taken into account. The scheme allows non-local mixing in unstable conditions by accounting for the increased vertical extent of turbulent eddies. The stability dependent transfer coefficients are calculated using Monin-Obukhov similarity theory, giving the surface fluxes of heat, moisture and momentum proportional to the surface-layer gradients. The local gradients with stability dependent transport coefficients, therefore, represent vertical transports (Smith, 1990). All near-surface variables of climatological interest (i.e., 1.5 m temperature and humidity, and 10 m winds) are diagnosed using the same approach. A stomatal resistance is prescribed to restrict evaporation from land and this restriction is further enhanced when the soil moisture content drops below a critical value.

6.4.3: Radiation

In general, the input provided to the radiative transfer calculation comprises the model's predicted temperature and moisture fields (and possibly ozone in some applications), together with fixed (climatological or perturbed) distributions of other active gas and aerosols. A radiative transfer scheme should include the distribution of surface albedo (climatological or predicted) and cloud cover (climatological or parameterized processes).

The scheme in the Unified Model (Ingram *et al.*, 1996) uses six spectral bands in the long wave calculation and four bands in the solar (short wave) calculation. Calculations depend on temperature, water vapour, ozone, carbon dioxide, and large-scale and convective cloud distributions. The seasonal and diurnal cycles of insolation are included in the scheme calculation.

Over the land, surface albedo in the Unified Model depends on snow depth and snow cover; both the values of snow-free and deep-snow albedos are accounted for in the calculations. The deep-snow albedo depends on vegetation and soil types, and surface temperature. Surface albedo is reduced to allow for multiple reflections between the surface and clouds.

A comprehensive calculation of the radiative transfer is highly complex due to the cloud feedback processes and distributions, which need to be parameterized in terms of model variables. The most uncertain element of the whole radiative parameterization is with prescription of cloud. Discussion of the radiative scheme in the Unified Model, therefore, should not be isolated from discussion of clouds (large-scale and convective), and will be given next in the following paragraphs.

6.4.4: Large-scale cloud and precipitation

The dynamical large-scale cloud calculations of the Unified Model use "vapour plus liquid and frozen cloud water", q_T, and "temperature adjusted to allow for the latent heat", T_L. These quantities are conserved under a variety of atmospheric processes (Smith, 1990). Cloud cover, then, is calculated from the difference, *D*, between q_T and the saturation specific humidity (Smith *et al.*, 1994), assuming a triangular subgrid-scale distribution of *D* about the grid-box mean value. Cloud water is assumed liquid above 0^oC, ice below -15^oC, and a mixture in between.

Large-scale clouds are represented in the scheme by their liquid water (or ice) content. Large-scale precipitation, therefore, is calculated in terms of the water or ice content of the cloud. Frozen (ice) cloud starts precipitating as soon as it forms and its precipitation is predicted by parameterizing the fall speed of ice particles in terms of in-cloud ice content. Ice particles, however, do not fall instantaneously to the ground, but contribute to the cloud water content of the layer below. For the liquid cloud, the scheme represents the coalescence and accretion processes as precipitation falls through the cloud. The scheme also includes cooling of the atmosphere due to evaporation of precipitation.

The scheme allows layer clouds to form at any level except at the top level. Allowance is made for greater efficiency of precipitation from clouds over sea compared with clouds over land. This difference is due to the differing size distributions of available cloud condensation nuclei (CCN).

The radiative properties of the cloud depend on cloud water and ice content. The total optical thickness of clouds is taken into account in the radiation calculations (Ingram *et al.*, 1996). Short wave cloud radiative properties depend on the cloud water path and effective droplet radius. Cloud radius is assumed to take value equal to 7 μm and 30 μm for water cloud and ice cloud respectively. Cloud is compounded into three layers (low, medium and high) for calculation of short wave fluxes, assuming random overlap between layers.

6.4.5: Convection

Convection parameterization, in general, is undertaken by producing a redistribution of heat and moisture in the vertical (and convective precipitation where appropriate) and based on parcel theory, modified by entrainment, and detrainment.

The Unified Model moist convection scheme, overall, considers the effect of convection on the large-scale atmosphere through compensating subsidence, detrainment, and evaporation of falling precipitation. From the original scheme (Gregory and Rowntree, 1990), a modified scheme with an explicit downdraught effect is now included (Gregory and Inness, 1996).

The updraught and downdraught processes are both accompanied by the effect of entrainment and detrainment of environmental air. In the updraught, the convective mass flux is calculated using parcel theory modified by entrainment and detrainment. The initial mass flux is assumed proportional to the stability of the lowest convecting layers. When a mixture of updraught and environmental air reach the highest model level, downdraught is then initiated and becomes negatively buoyant on descent to the next level below. In another words, the downdraught is an inverted entraining plume. It is cooled by evaporation of precipitation. A detrainment occurs once the downdraught descends to a level at which it is positively buoyant or reaches the surface.

Convective precipitation is determined from the convective cloud amount. To achieve the calculation of precipitation, the cloud amount is calculated using a logarithmic dependence on total cloud condensate, by removing cloud condensate above a specified threshold, provided the cloud exceeds a critical depth. The critical depth over land and sea is 4 km and 1.5 km respectively, following the nature of differing distribution of cloud condensation nuclei. A critical value of 1 km, however, is used when the cloud top temperature is less than -10^{o}C. This is to allow for precipitation caused by the growth of hail from freezing of supercooled water droplets.

6.4.6: Gravity-wave drag

In general terms, a parameterization of gravity-wave drag is applied at upper levels, but calculated from low-level wind and static stability and the variability (variance) of orographic height within each grid box. The basic elements of the scheme are the determination of a “surface” stress related to the subgrid-scale orography and the vertical distribution of the atmospheric stress (Wilson and Swinbank, 1991). The scheme, therefore, is to estimate the effects of the drag caused by subgrid-scale gravity waves, using subgrid variance of the orography and known absorption properties of gravity waves in a given atmospheric profile.

Overall, the scheme is split into two parts: one calculates the “surface” stress and the other deals with the wave-breaking aspects. According to Wilson and Swinbank, the scheme currently used in the Unified Model is a simple parameterization of orographic gravity-wave drag. To improve the scheme, there is a lot of scope for further refinements, needing further development to include additional effects such as wave reflection, wave trapping and storm-generated (convective) gravity waves.

6.4.7: Eddy diffusion

Recall that this parameterization is actually related to the term K_x which appeared in the forms of primitive equations discussed earlier in Section 6.3. The term is usually included in models to prevent an unrealistic growth of the smallest resolved scales by representing the influence of unresolved scales of motion on the explicitly predicted scales. It is common to choose empirically a computationally convenient form of smoothing to represent the unresolved scale of motion, and to adjust it so that contour plots of the predicted variables do not appear excessively rough. As atmospheric motion involves both horizontal and vertical components, this parameterization, therefore, can be divided into two schemes: the first one is called horizontal eddy diffusion; and the second is vertical eddy diffusion.

For the horizontal eddy diffusion, the smoothing is carried out using simple grid-scale filters, by which the filters can be iterated to make them more scale selective for use at low resolution (Cullen *et al.*, 1993). The vertical eddy diffusion is sometimes required to remove oscillations caused by inadequately resolved quasi-inertia waves. For the vertical eddy diffusion scheme in the Unified Model, only the winds are smoothed (Wilson, 1992).

6.4.8: Ancillary fields

Fields involved in the Unified Model are either of prognostic variables or of ancillary fields. As documented (Cullen, 1993; Dickinson, 1994), the primary prognostic variables predicted by the atmosphere models of the Unified Model are: horizontal wind components; potential temperature; specific humidity; cloud water and ice; surface pressure; soil temperature; soil moisture content; canopy water content; snow depth; and surface temperature. The diagnosed secondary prognostic variables are: boundary layer depth; sea surface roughness; convective cloud amount; convective cloud base; convective cloud top; layer cloud amount; and vertical velocity. The above prognostic variables, however, cannot be obtained without the presence of other specified ancillary fields in the model.

In the Unified Model, the parameters to be specified as ancillary fields when running in the atmosphere-only mode are: sea surface temperature; proportion of sea-ice cover; sea-ice thickness; and sea surface currents. These variables, however, are included as additional prognostic variables when running in coupled ocean/atmosphere configurations. There are some ancillary fields, which must be specified because they are not predicted at all, whether in atmosphere-only mode or coupled ocean/atmosphere models. They are a land/sea mask; soil type; vegetation type; and grid-box mean and variance of orography. Although ozone mixing ratio is usually specified as an ancillary field, but it may also be a prognostic variable for some applications.

Values of those ancillary fields, which mainly come from surface parameters, are required for surface exchange calculations. For example, in atmosphere-only mode, sea-surface temperatures are specified from analyses updated at certain time intervals and sea-ice cover is specified from climatology, supplemented by observational data where available.

6.5: Software System, Sub-Models and Model Coupling

This summary of the software implementation and various types of available coupling given below is based on Cullen (1993), as well as the Unified Model User Guide (Met. Office, 1996).

6.5.1: Software implementation

The Unified Model software system can be divided into five main components. An overall connection between the five components is shown in Figure 6.4.

(i) *User interface:* This is a panel-driven system, which allows a user to run any version of the model with any choice of diagnostic output. The system holds a library of previous experiments. To conduct new experiments, only small changes based on previous experiments are needed. A useful alternative starting point, therefore, can be obtained from a set of standard experiments held by the system, rather than setting up a new experiment from scratch.

(ii) *Reconfiguration:* This module processes the model's initial data. It acts as a conversion system, which converts an input data set to a new resolution, allowing the horizontal or vertical resolution of the data to be changed. The creation of a limited area region is also carried out from this module. New ancillary or analysed data may also be incorporated into the initial data. This imported and expanded data would allow extra diagnostics. Within this module, fields such as the specification of the height of orography or land-sea mask may be overwritten with appropriate values, whenever the horizontal resolution is changed. This module, in addition, has the ability to incorporate ensemble perturbations, tracer fields and the transplanting of prognostic data.

(iii) *Model:* This may be atmosphere-only, ocean-only, coupled atmosphere-ocean, or coupled with sub-models. The ocean model solves equations for the motion of the ocean. The ocean model solution, similar to those used in the atmospheric component, is also based on a

finite difference representation with a spherical coordinate system in the horizontal. In the vertical, however, instead of the hybrid system, only a geometric depth is used by the ocean model. A summary of coupling types (e.g., atmosphere-ocean and other sub-models) will be given separately later. The atmosphere and/or ocean model, if required, may also be integrated with data assimilation. It is performed using an analysis correction scheme (an iterative analysis), with each variable being analysed in turn. In the data assimilation mode, each iteration is interleaved with a timestep of the full forecast model to nudge the forecast model solution towards observations.

(iv) Spatial and Temporal Averaging and Storage Handling (STASH): This is also sometimes referred to as “Storage Handling and Diagnostic System”. This system is for diagnosing data generated in each section of the model. Diagnostic data output from the model may be defined and output on a timestep by timestep basis. Depending on user requirements, data is either output to the front-end computer or retained for later time averaging. The output data may be in the form of horizontal fields, sub-areas or timeseries, along with the accumulation, and time or spatial meaning of fields. Separate post-processing of classes of diagnostics are also facilitated by splitting across a number of files.

(v) Output streams: Different streams of output depending on requirements can be requested. The streams could be for coupling to other models, dumps to allow integrations to be restarted, and output data for charts.

6.5.2: Sub-models and coupling

The Atmospheric Model and the Ocean Model are the two main sub-models available within the Unified Model. Each of them can be run in single mode, atmosphere-only or ocean-only. In addition to those main sub-models, various types of coupled models and other sub-models are available.

(i) Atmosphere-Ocean coupled model: The atmosphere model can be coupled to both global and limited-area ocean models. On a global domain, a sea-ice sub-model may be

embedded in the ocean sub model (This is the main configuration for climate change simulations).

(ii) *Atmosphere-Slab coupled model:* The atmosphere model can be coupled to a highly simplified ocean model known as a ‘slab’ model. On a global domain, a sea-ice sub-model is included as part of the slab ocean (primarily used for short climate sensitivity experiments).

(iii) *Stratosphere-only model:* A version of the Unified Model covering only the stratosphere can be obtained using a full atmosphere model to generate the heights of an isobaric surface. As an example, for middle atmosphere research, daily analyses of the stratosphere are carried out at the UKMO using a version of the Unified Model’s data assimilation scheme.

(iv) *Limited-area model:* A limited-area (regional) domain is driven by the global atmosphere model that provides values of the prognostic variables in a boundary zone (further discussion is given in Appendix A). A similar method is used to drive a mesoscale model from the regional model.

(v) *Wave and surge models:* The wave model is driven by 10 metre winds output from the atmosphere model and the surge model is driven by model surface pressure and wind output.

6.6: Summary

The overview of the history, basis of its design and numerical formulation as well as software system of the Unified Model provides a fundamental knowledge useful for employing the model for this area of study. In term of the numerical formulation introduced, the general introduction on parameterizations has given a basic understanding on the important of unresolved small-scale processes to be included in the model. In the next chapter, the land surface scheme of the Unified Model is described, as an extension to the point introduced in this chapter.