NL3617 General circulation models of the atmosphere

Atmospheric general circulation models (AGCMs) simulate the dynamical, physical and chemical processes of planetary atmospheres. For the Earth's atmosphere (see the entry *Atmospheric and ocean sciences*) they are based on the thermo-hydrodynamic equations, which consist of the conservation of momentum, mass and energy with the ideal gas law in coordinates suitable for the rotating planet.

In the presently used form they were first derived by V. Bjerknes in 1904; subsequently L. F. Richardson (1922) proposed numerical weather prediction (NWP) as a practical application which, in 1950, was successfully performed by Charney, Fjørtoft and von Neumann based on a simplified set of these equations. While numerical weather prediction models utilize the atmospheric short-term memory for forecasting, AGCMs developed since the 1960s extend applications to longer time scales simulating seasonal and climate variability (for a personal recollection see Smagorinsky (1983)).

Since then numerical weather prediction and atmospheric general circulation modeling has enjoyed continuous advances, which are attributed to the following gains and improvements: (1) observational data accuracy, analysis and assimilation, (2) insight into dynamical and physical processes, numerical algorithms and computer power and (3) the use of model hierarchies to study individual atmospheric phenomena. With simulations of the Earth system and that of other planets envisaged, a broad field of science has been established, which is of vital importance socio-economically, agriculturally, politically and strategically.

(1) Observations

Since the foundation of the World Meteorological Organization (WMO) and international treaties to monitor and record meteorological and oceanographical data, the collection of global data through local weather and oceanic stations has been systematically organized and has become a truly globalized system through the deployment of satellites and introduction of remote sensing facilities. The availability of extensive global data has enabled the extension of NWP models to complex global

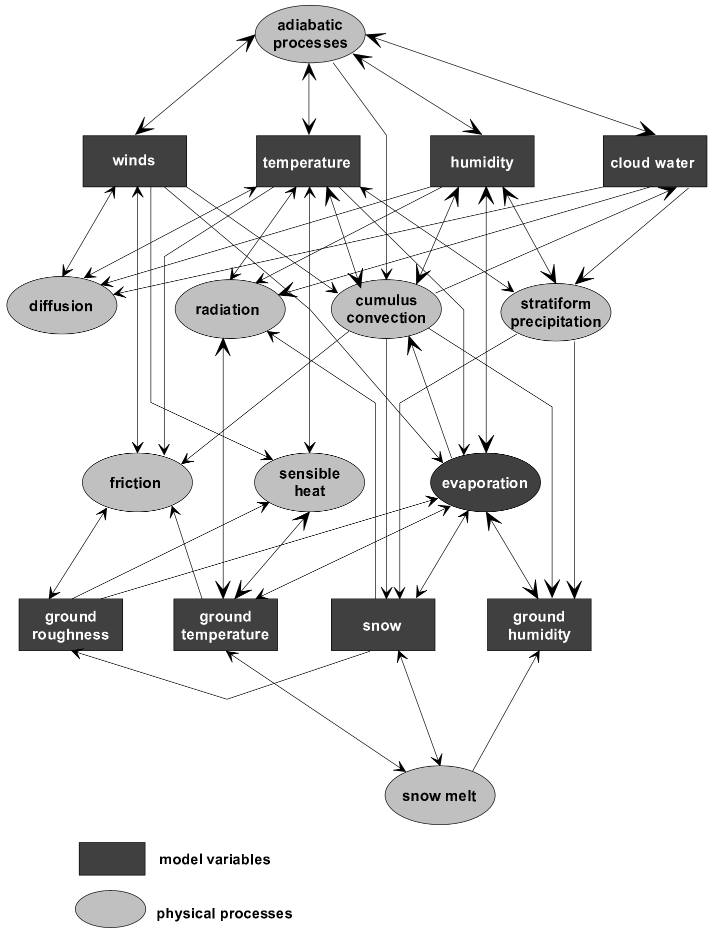

Figure 1. Interactions in comprehensive GCMs (schematic).

GCMs, thus facilitating simulations on larger timescales (months and years instead of hours and days) and validation of NWPs in return. Furthermore, it has become possible to study climate history and make estimates of future climates, which is particularly important due to the likely impact of anthropogenic nature.

(2) General circulation models

Atmospheric general circulation models have two basic components. First, the dynamical core consists of the primitive equations (the conservation equations with vertical momentum equation approximated by hydrostatic equilibrium, that is balancing the vertical pressure gradient and the apparent gravitational forces) under adiabatic conditions. Secondly, physical processes contribute to the diabatic sources and sinks interacting with the dynamical core. They are incorporated as parameterizations, mostly in a modular format: solar and terrestrial radiation, the hydrological cycle (with phase transitions manifested in evaporation and transpiration, cloud and precipitation processes), the planetary boundary layer communicating between the free atmosphere and the ground (soil with vegetation, snow and ice cover; ocean with sea ice), and air-chemistry. Most of these parameterizations enter the thermodynamic energy equation as heat sources or sinks.

(2.1) Dynamical core:

State of the art atmospheric general circulation models commonly utilize the so called primitive equation approximation of the Navier–Stokes equations. In addition to the dry dynamics, equations describing the transport of other constituents like water vapour, cloud liquid water and ice, trace gases and particles (aerosols) can be an integral part of the dynamical core. To integrate the equations they are discretized in space and time where finite differences and spectral methods are the most dominant. For more details on the governing equations please refer to the entries for *Atmospheric and ocean sciences*, *Fluid Dynamics* and *Navier–Stokes equation*.

(i) Horizontal discretization: In the horizontal, grid point or spectral representations of the dependent model variables are used. Different grid structures and finite difference schemes have been designed to reduce the error (Messinger and Arakawa (1976)). An alternative approach is the spectral method. The dependent variables are represented in terms of orthogonal functions where appropriate basis functions are the spherical harmonics. The maximum wave number of the expansion defines the resolution of the model. Since the computation of products is expensive only linear terms are evaluated in the spectral domain. To compute the nonlinear contributions, the variables are transformed into grid point space every time step, where the respective products are computed and transformed back to spectral space. Necessary derivatives are computed during the transformation. This spectral-transform procedure (Eliassen *et al* (1970); Orszag (1970)) makes the spectral approach computationally competitive with finite difference schemes. For low resolutions, the spectral method is in general more accurate than the grid point method. However, in particular the treatment of scalar fields which exhibit sharp gradients and, for physical reasons, must maintain a positive definite value (e.g. water vapour, cloud water, chemical tracers), spectral methods are less suitable. Therefore, selected fields are often treated separately in the grid point domain using, for example, semi-Lagrangian techniques. Recently, with increasing model resolutions and the need of transporting more species (e.g. for chemical sub-models), grid point models are attracting more attention again, while novel grid structures are introduced such as for instance the spherical icosahedral grid of the German Weather Service model GME (Majewski *et al* (2000)).

(ii) Vertical discretization: In general, finite differences and numerical integration techniques are used for the derivatives and integrals in the vertical. The vertical coordinate can be defined in different ways. The isobaric coordinate eliminates the density from the equations and simplifies the continuity equation compared with a z-coordinate system. However, the intersection of low level pressure surfaces by the orography enforces time dependent lower boundary conditions which are difficult to treat numerically. This problem can be avoided if terrain following sigma (σ) coordinates are used, where sigma is defined by the pressure divided by the surface pressure $\sigma = p/p_0$. Unfortunately, the sigma coordinate leads to a formulation of the pressure gradient force which, in the presence of steep orography, is difficult to treat. The advantages of both, sigma and pressure coordinates, are combined by introducing a hybrid coordinate system with a smoothed transition from σ to p with height.

(2.2) Physical processes and parameterizations:

Many processes which are important for the large scale atmospheric flow cannot be explicitly resolved by the model due to its given spatial and temporal resolution. These processes need to be parameterized, that is, their effect on the large scale circulation is formulated in terms of the resolved grid-scale variables. The most prominent processes building a parameterization package of an atmospheric general circulation model are long– and short–wave radiation, cumulus convection, large scale condensation, cloud

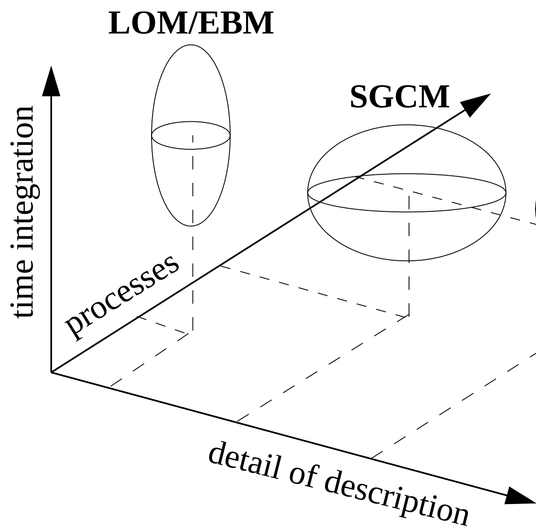

Figure 2. A model hierarchy of general circulation models.

formation and the vertical transport due to turbulent fluxes in the planetary boundary layer and the effect of different surface characteristics such as vegetation on the surface fluxes. Additional processes like the excitation of gravity waves and their impact on the atmospheric momentum budget or the effect of vertical eddy fluxes above the boundary layer are mostly considered. Since the land surface provides a time dependent boundary condition which acts on time scales comparable to the atmosphere, great effort has been made to include land surface and soil processes in the atmospheric parameterization package. More recently the effect of the interaction of various chemical species and their reactions with the atmospheric circulation are also being considered. In addition to the direct relation between the resolved atmospheric flow and the effect of the parameterized processes, there are various other interactions among the individual processes which have to be taken into account. For typical comprehensive atmospheric general circulation models Figure 1 displays the interrelations between the adiabatic dynamics providing the spatial and temporal distribution of the dependent model variables and the various processes being parameterized.

(3) Model hierarchy

General circulation models of reduced complexity are continuously developed to supplement comprehensive GCMs, to gain insight into atmospheric phenomena (see Figure 2) and for educational purposes: When utilizing the full set of equations, the model spectrum ranges from simple GCMs (SGCMs) with analytic forms of heating and friction to low-order models (LOMs). A prominent LOM is the Lorenz model (see entry on *Lorenz model*), which approximately describes the nonlinear convection dynamics in the vicinity of a critical point for the streamfunction and temperature in a set of ordinary differential equations. It can be regarded as including first order nonlinear effects to a linear model and exhibits chaotic behaviour. The Lorenz model is used to study predictability and serves as a paradigm for phase–space behaviour of atmospheric GCMs. Utilizing thermal energy conservation only, another spectrum of models (EBMs or energy balance models) are obtained by averaging in certain spatial directions. These lead to the horizontally averaged one-dimensional radiative-convective models; the one-dimensional energy balance model when averaged vertically and longitudinally for studying climate feedback and stability, and two-dimensional statistical-dynamical models when averaged longitudinally where dynamical processes are being parameterized. A prominent EBM example is the globally averaged or zero–dimensional energy balance model. With ice-albedo and water vapour-emissivity feedbacks included, climate catastrophes leading to a snowball–earth and run–away greenhouse can be demonstrated; with random forcing and periodic solar radiation input (e.g. Milankovich cycles) stochastic resonance emerges.

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See also: Atmospheric and ocean sciences, Fluid Dynamics, Lorenz model, Navier–Stokes equation

Further Reading

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