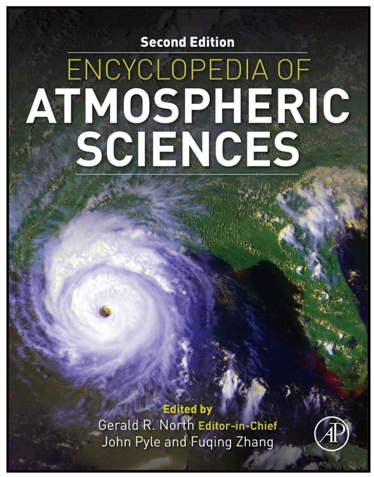




From Pielke Sr., R.A., 2015. Mesoscale Atmospheric Modeling. In: Gerald R. North (editor-in-chief), John Pyle and Fuqing Zhang (editors). Encyclopedia of Atmospheric Sciences, 2nd edition, Vol 4, pp. 219–221.
ISBN: 9780123822253

Academic Press

# Mesoscale Atmospheric Modeling

**RA Pielke, Sr.,** University of Colorado at Boulder, CO, USA



## Synopsis

Mesoscale systems in the atmosphere are those in which the instantaneous pressure field can be determined accurately by the temperature field, but the winds, even in the absence of surface frictional effects, are out of balance with the horizontal pressure gradient force. The framework of mesoscale models is overviewed and shows that the models include a physics base core comprising the pressure gradient force, advection, and gravity, and all other physical processes that are parameterized using tuned modular representations of turbulence, longwave and shortwave radiation, cumulus, and stable cloud processes. Computational methods, lateral and initial boundary conditions, and model validation are some of the topics discussed.

## Introduction

Atmospheric mesoscale systems are identified as those in which the instantaneous pressure field can be determined accurately by the temperature field, but the winds, even in the absence of surface frictional effects, are out of balance with the horizontal pressure gradient force. The pressure field, under this situation, is said to be 'hydrostatic.' Larger scale atmospheric features (which are called 'synoptic' weather features), in contrast, have a wind field that is close to a balance with the horizontal pressure gradient force. These large-scale winds are said to be near gradient wind balance. Atmospheric features that are smaller than the mesoscale have pressure fields in which wind acceleration is a significant component (which is referred to as the dynamic wind). The pressure gradient that causes this dynamic wind is called the nonhydrostatic pressure.

Atmospheric mesoscale models are based on a set of conservation equation for velocity, heat, density, water, and other trace atmospheric gases and aerosols. The equation of state used in these equations is the ideal gas law. The conservation of velocity equation is derived from Newton's second law of motion as applied to the rotating Earth. The conservation of heat equation is derived from the first law of thermodynamics. The remaining conservation equations are written as a change in an atmospheric variable (e.g., water) in a Lagrangian framework where sources and sinks are identified.

Each of these conservation equations can be written to represent the changes following a parcel of velocity, potential temperature (entropy), water in its three phases, other atmospheric gases and aerosols, and mass, including source–sink terms. Models, however, seldom express the conservation relations in a Lagrangian framework. The chain rule of calculus is used to convert to an Eulerian framework.

Several assumptions are typically made in the conservation equations. These include the neglect of small-scale fluctuation of density except when multiplied by gravity (this is called the Boussinesq approximation), the neglect of vertical acceleration relative to the differences between the vertical pressure gradient force and gravity (referred to as the hydrostatic assumption), and the neglect of all molecular transfers.

The first two assumptions have not been made in recent years in the models, however, since the numerical equations are actually easier to solve without these assumptions. Nonetheless, the spatial and temporal scales of mesoscale systems result in the two assumptions being excellent approximations with respect to mesoscale-sized systems. The third assumption is justified since advection is much more significant at transfers of heat, momentum, water, and other chemical species, than molecular motion on the mesoscale.

These conservation relations that are written as a set of simultaneous, nonlinear differential equations, unfortunately, cannot be used without integrating them over defined volumes of the atmosphere. These volumes are referred to as the model 'grid volume'. The region of the atmosphere for which these grid volumes are defined is called the 'model domain.' The integration of the conservation relations produces 'grid volume averages,' with point-specific values of the variables called 'subgrid-scale values.' The 'resolution' of data is limited to two grid intervals in each spatial direction.

The result of the grid volume averaging produces equations for the local time derivative of the grid volume-resolved variable which includes 'subgrid-scale fluxes.' An assumption that is routinely made in all mesoscale models (usually without additional comment) is that the gird volume average of subgrid-scale fluctuations is zero. This assumption, often referred to as 'Reynold's averaging,' is actually only accurate when there is a clear spatial scale separation between subgrid scale- and grid volume-resolved quantities.

Mesoscale model equations have been solved in a Cartesian coordinate framework. Each coordinate in this system is perpendicular to the other two coordinates at every location. Most mesoscale models, however, transform to a generalized vertical coordinate. The most common coordinates involve some form of terrain-following transformation, where the bottom coordinate surface is terrain height or terrain surface pressure. The result of these transformations is that the new coordinate system is not orthogonal, in general. Unless this nonorthogonality is small, the correct treatment of nonhydrostatic pressure effects in mesoscale models requires the use of tensor transformation techniques, as opposed to the separate use of the chain rule on each component of velocity, separately. The use of generalized coordinate systems introduces additional sources for errors in the models, since the interpolation of variables to grid levels becomes more complicated.

The model variables also need to be defined on a specified grid mesh. When all dependent variables are defined at the same grid points, the grid is said to be 'nonstaggered.' When dependent variables are defined at different grid points, the grid



Encyclopedia of Atmospheric Sciences, Second Edition, 2015, 219–221

is called a 'staggered grid.' The grid meshes can also be defined with smaller grid increments in one region surrounded by coarser grid increments. Such a grid is referred to as a 'nested grid.' If the grid increments vary at all locations, with the finest grid in a specified volume, the grid is called a 'stretched grid.'

The subgrid-scale fluxes in mesoscale models are parameterized in terms of resolvable variables. Turbulence theory, as observed from atmospheric field campaigns over horizontally homogeneous landscapes, and for undisturbed atmospheric conditions, is the basis for all mesoscale model representations of the vertical subgrid-scale flux terms. The vertical fluxes are parameterized differently when the lowest 50 m or so of the atmosphere are unstably stratified and when it is stably stratified. The planetary boundary is typically represented by three layers: a thin layer of a few centimeters near the surface where laminar fluxes are important (called the 'laminar layer'), a layer above which extends upward tens of meters where wind direction with altitude is ignored (referred to as the 'surface layer'), and the remainder of the boundary layer where the winds approach the free atmospheric value (referred to as the 'transition layer'). Disturbed (unsteady) boundary layers are not parameterized accurately, however, by existing parameterizations. The effect of land surface heterogeneity has been included on the subgrid scale only as a weighting of the surface layer fluxes by the fractional coverage of each land surface type. This technique is called the 'mosaic' or 'tile' subgrid-scale surface flux parameterization.

In contrast to the vertical fluxes, horizontal subgrid-scale fluxes in mesoscale models have no physical basis. They are included only to horizontally smooth the model calculations.

The representation of the source–sink terms in the conservation equations can be separated into two basic types: those that are derived from basic concepts and those that are parameterized. The only basic source–sink terms in mesoscale models that are derived from fundamental physical concepts are the pressure gradient force, advection, and gravity. Neither of these two effects involves adjustable (i.e., tunable) coefficients, which is one method to separate fundamental terms in the conversation equation from a parameterization. The remainder of the source–sink terms needs to be parameterized. Almost all parameterizations currently used in these models are either box or vertical column representations.

The radiative flux terms are typically separated into shortwave and longwave fluxes. The shortwave fluxes, also called 'solar fluxes,' are separated into direct and diffuse irradiance. The direct irradiance is the nonscattered flux, whereas the diffuse irradiance is the scattered radiative flux from the Sun. The direct irradiance is sometimes further separated into visible and near-infrared components. In cloudy model atmospheres, parameterizations based on cloud liquid water content, or more crudely on arbitrary attenuation based on relative humidity in the model, are used. Typically, only diffuse irradiance is permitted for overcast model conditions. Some models weight the fluxes for partly cloudy skies, using weighted parameterizations for both clear and overcast sky conditions. Polluted atmospheres also require parameterization on their effect on solar irradiance, although only a few mesoscale models have explored this issue.

Longwave irradiance is from the Earth's surface and from within the atmosphere. Scattering of longwave radiative fluxes is typically ignored, such that only upwelling and downwelling irradiances are parameterized. This type of parameterization is called a 'two-stream approximation.' The major absorbers and emitters represented in mesoscale model parameterizations are liquid and ice clouds, water vapor, and carbon dioxide. Clouds are usually parameterized as black bodies to longwave irradiance. The wave vapor and carbon dioxide are represented by the path length through the atmosphere, and their concentrations along their path. As with solar radiative fluxes, mesoscale models seldom includes parameterizations of longwave irradiance associated with pollution. This neglect is partially a result of the dependency of the absorption, transmissivity, and scattering of both solar and longwave irradiance on the specific chemical composition and size spectra of the pollution.

The phase changes of water and this effect on the conservation of heat source–sink term are separated into stable cloud, cumulus convective cloud, and precipitation parameterizations. Stratiform cloud parameterizations range in complexity from algorithms which instantaneously precipitate rain (or snow) when the model relative humidity exceeds a user-specified relative humidity (referred to as a 'dump bucket' scheme), to individual conservation equations for several categories of hydrometers (e.g., cloud water, rain water, ice crystals, snow, graupel, and hail). For the larger hydrometeors, a nonzero, finite terminal fall velocity is usually specified. More detailed microphysical representations, where cloud hydrometer spectra are classified into more size class intervals (called 'microphysical bin parameterizations') are also used.

The parameterization of cumulus cloud rainfall utilizes some form of one-dimensional cloud model. These are called 'cumulus cloud parameterization schemes.' Their complexity ranges from instantaneous readjustments of the temperature and moisture profile to the moist adiabatic lapse rates when the relative humidity exceeds saturation, to representations of a set of one-dimensional cumulus clouds with a spectra of radii. These parameterizations typically focus on deep cumulus clouds, which produce the majority of rainfall and diabatic heating associated with the phase changes of water. Cumulus cloud parameterizations remain one of the major uncertainties in mesoscale models, since they usually have a number of tunable coefficients, which are used to obtain the best agreement with observations. Also, since mesoscale model resolution is close to the scale of thunderstorms, care must be taken so that the cumulus parameterization and the resolved moist thermodynamics in the model do not 'double count' this component of the source–sink terms.

The grid volume-averaged conversation equations are nonlinear and, therefore, must be solved using numerical approximation schemes. The solution techniques include finite difference, finite element, interpolation (also called semi-Lagrangian), and spectral methods. Both temporal–spatial terms and the source–sink terms must be represented by these approximation schemes. An important aspect of mesoscale models is that only advection and the pressure gradient force involve horizontal gradients explicitly. All other model terms, including each of the source–sink terms, are one-dimensional column models or point values.

Finite difference schemes involve some form of truncated Taylor series expansion. The finite element technique uses a local basis function to minimize the numerical error, whereas the spectral method utilizes global basis functions. A spectral method has the advantage that differential relations are converted to algebraic expressions. The semi-Lagrangain scheme is based on fitting interpolation equations to data at a specific time and advecting the data with model winds.

Mesoscale models have predominately utilized the finite difference and (for advection) the semi-Lagrangian approaches. A few groups have applied the finite element method, but its additional computational cost has limited its use. The spectral method, which is most valuable for models without lateral boundaries, has not generally been used since mesoscale models have lateral boundaries.

The use of numerical approximations introduces errors. Linear stability analyses show that it is impossible to create a numerical solution scheme which accurately represents both amplitude change over time and speed of motion (advection and gravity wave propagation) for features that are shorter than about four grid increments in each spatial direction. In addition, products of the variables (which are a nonlinear terms) produce transfers of spatial scales to larger and smaller scales. The inability of the numerical model to sample the smallest scales (less than two grid intervals) results in the information (e.g., winds and temperature) erroneously appearing at a larger spatial scale. This error is called 'aliasing' and unless corrected can result in an incorrect accumulation of atmospheric structure at the wrong spatial scale. For these reasons, the term 'model resolution' should be reserved for features that are at least four grid intervals in each direction.

To integrate the models forward in time, the variables must be initialized. These values are called 'initial conditions.' Observed data, or a combination of observed data and previous model calculations, are typically used to initialize the mesoscale models. The insertion of data during a model calculation is called 'four-dimensional data assimilation (4DDA).' Lateral, top, and bottom boundary conditions are also needed for the duration of the model calculations. Lateral boundary conditions in mesoscale models can be idealized for theoretical studies (e.g., cyclic boundary conditions), or derived from large-scale observations, such as the NCEP Reanalysis or from larger scale model simulations (which is referred to as dynamic downscaling). Mesoscale models are often strongly influenced by the lateral boundary conditions, such that their accurate representation is a necessary condition for an accurate mesoscale simulation.

The top boundary conditions are similar to the lateral boundary condition and must be accurately represented. Most mesoscale models extend into the stratosphere, in order to minimize the effect of the model top on the mesoscale simulation. Damping zones at the model top (referred to as an 'absorbing layer') are usually inserted so that upward propagating model simulated gravity waves do not erroneously reflect from the artificial model top.

The surface boundary is the only surface of a mesoscale model which is physically based. This surface is typically separated into ocean (and fresh water lakes) and land surfaces. Ocean and lake surfaces can be represented simply as prescribed sea surface temperatures or using mesoscale atmospheric models coupled to mesoscale ocean, lake, and/or sea ice models. Over land, the ground is separated into bare soil and vegetated land. Soil–vegetation–atmosphere transfer schemes (SVATS) have been introduced to represent the fluxes of velocity, heat, moisture, and other trace gases between the atmospheres and the surface. Most SVATS include the effect on water flux of transpiration. Recently, vegetation dynamical processes, such as plant growth have been included in longer term (months to seasons) mesoscale model calculations.

Model performance is assessed in several ways. The comparison of observations with model results using statistical skill tests is a major assessment tool. A complication of these evaluations is that observations have a different sampling volume (e.g., a point) than the model grid volume. Comparisons of simplified (usually linearized) version of numerical models with analytic theory have been completed to test the accuracy of linear components of the model. Several models can be intercompared to assess what features they have in common, and which they do not. The mass and energy budgets of the mesoscale models, if they are each calculated in two separate manners, provide an opportunity to check the internal consistency of the model. Peer-reviewed scientific publications and the availability for scrutiny of the model source code provide two additional valuable procedures to assess the value of the mesoscale model and the degree to which the programmed model logic agrees with the mathematical formulations presented in the literature. Proposals have been made to standardize the model computer codes, in order to assist in their more general use.

Mesoscale models have been applied to two basic types of mesoscale systems: those found primarily by initial and lateral boundary conditions (referred to as synoptically forced mesoscale systems) and those forced by surface boundary conditions (referred to as surface-forced mesoscale systems). Of the latter type, there are mesoscale systems that are caused when terrain is an obstacle to the flow (referred to as 'terrain-forced' or orographic mesoscale systems) and those generated by horizontal gradients in sensible heating of the surface (called 'thermally forced' mesoscale systems).

With the improvement in computational power, global models will soon approach mesoscale spatial and temporal resolution (which requires horizontal grid increments of $\sim$1 km). This high resolution will eliminate lateral boundary conditions as a component in the accurate simulation of mesoscale atmospheric features models.

## Further Reading

Cotton, W.R., Bryan, G., Van den Heever, S., 2009. Storm and Cloud Dynamics. In: International Geophysics, second ed. vol. 99. Academic Press.

Fedorovich, E., Rotunno, R., Stevens, B. (Eds.), 2004. Atmospheric Turbulence and Mesoscale Meteorology. Cambridge University Press.

Kalnay, E., 2003. Atmospheric Modeling, Data Assimilation and Predictability. Cambridge University Press.

Pielke Sr., R.A., 2002. Mesoscale Meteorological Modeling, second ed. Academic Press, San Diego, CA.

Pielke, R.A., 2013. Mesoscale Meteorological Modeling, third ed. Academic Press, San Diego, CA.

Pielke Sr., R.A., Stokowski, D., Wang, J.-W., Vukicevic, T., Leoncini, G., Matsui, T., Castro, C., Niyogi, D., Kishtawal, C.M., Biazar, A., Doty, K., McNider, R.T., Nair, U., Tao, W.K., 20 February 2007. Satellite-based model parameterization of diabatic heating. EOS, vol. 88 (8), 96–97.

Warner, T., 2011. Numerical Weather and Climate Prediction. Cambridge University Press.

Whiteman, C.D., 2000. Mountain Meteorology Fundamentals and Applications. Oxford University Press.