

History of, Processes in, and Numerical Techniques in GATOR-GCMOM

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Background

GATOR-GCMOM is a gas, aerosol, transport, radiation, general circulation, mesoscale, and ocean model.

In 1990, the model was developed as GATOR, a regional-scale gas, aerosol, radiation, and transport model that accounted for multiple discrete aerosol size distributions (containing size bins) and the effects of size-resolved aerosols on photolysis.

In 1993, meteorology and feedback of gases and size-resolved aerosols to meteorology through solar and thermal-IR radiative transfer were added. The result was the first online, coupled regional air quality-meteorological model worldwide, GATORM (also called GATOR-MMTD).

In 1994, a global version of the model that included gases, aerosols, radiation, transport, and meteorology was first developed, accounting for the same processes as in the mesoscale model. The global version was GATORG, which treated gas photochemistry, size- and composition-resolved aerosol processes, spectral radiative transfer, and their feedback to meteorology. As such, this was the first online, coupled global air quality-weather-climate model worldwide.

Starting in 1998, the global and regional versions of the model were linked together, and the result was the first nested, online, coupled global-through-urban scale air quality-weather-climate model, GATOR-GCMM. This model accounted for nesting of all processes treated in GATORM and GATORG. Subgrid surface parameterizations were added and aerosol numerics, including treatment of aerosols among multiple size distributions, were improved. All processes in all nested grids were exactly the same, except for the different horizontal boundary conditions and solutions to the momentum equation on the global versus regional scale.

In 2000, treatment of multiple size distributions of discrete size-resolved cloud hydrometeors containing aerosol inclusions, and interactions between these hydrometeors and multiple size distributions of discrete size-resolved aerosols were added. The result

was the first online-coupled air quality-weather-climate model to treat discrete size- and composition-resolved clouds.

In 2001, a 2-D ocean module was added, and the resulting module was GATOR-GCMOM. In 2004 3-D ocean equilibrium chemistry and diffusion of all chemicals and energy were added, making GATOR-GCMOM the first coupled atmosphere-ocean model to treat 3-D ocean equilibrium chemistry explicitly.

In 2004, the 3-D evolution and transport of grid-scale clouds on the regional scale was added, as was a new method of calculating heating rates for multiple absorbing greenhouse gases simultaneously.

In 2007, the treatment of the evolution of aircraft exhaust from all commercial aircraft flights worldwide at the subgrid scale was added.

In 2009, near-explicit photochemistry (over 4600 species and 13,500 reactions) and transport, radiative heating and photolysis of all explicit gases were added. GATOR-GCMOM became the first atmospheric model to simulate 3-D near-explicit photochemistry on single and multiple atmospheric scales.

Table 1 compares treatment of online coupling of gas, aerosol, radiative, transport, and meteorological processes in GATOR-GCMOM with that in prior or concurrent models that treated any coupling. Whereas, several 3-D models had some form of coupling, none prior to GATOR-GCMOM (a) transported all photochemically-active gases explicitly, (b) solved time-dependent chemistry for all photochemically-active gases, or (c) treated feedback to heating rates or photolysis coefficients of all time-varying, absorbing gases, all discrete, size-resolved aerosol particles, or all discrete, size- and composition-resolved hydrometeor particles.

Table 1. Comparison of treatments of online coupling of gas, aerosol, radiative, transport, and meteorological processes between GATOR-GCMOM (in red) and other prior or concurrent models treating any coupling.

	H69	C70 S79	C74	A75 Jo76 T85 C85 M86	P84 G91 R95	P92	J94c J95c J96b J97a J97b	J02b J04a J04b J04c J04d	J06b J07b	J09c
3-D transport, driven by online meteorology, of										
ozone	Y	Y				Y				
ozone and some other gases and families, but not all photochemically-active gases					Y					
all photochemically-active gases							Y	Y	Y	Y
All photochemically-active gases (4675) in near-explicit mechanism										Y
single bulk or modal aerosol				Y						
all discrete, size-resolved aerosol particles							Y	Y	Y	Y
all chemicals within discrete, size-							Y	Y	Y	Y

resolved aerosol particles										
all discrete, size-resolved hydrometeor particles and their aerosol inclusions									Y	Y
Gas chemistry solved online with meteorology and gas transport										
None				Y						
Time-dependent for ozone only	Y	Y	Y			Y				
Time-dependent for ozone and some gases; steady-state or family chemistry for others gases					Y					
Time-dependent for all reacting and transported gases							Y	Y	Y	Y
Time-dependent for near-explicit photochemistry (4675 transported and reacting gases, 13,626 reactions)										Y
Online feedback of chemically-varying gases or particles to heating rates for driving meteorology										
No feedback	Y				Y					
Feedback of online ozone to lookup-table heating rate			Y							
Feedback of online ozone to online parameterized heating rate		Y				Y				
Feedback of all photochemically-reacting gases to heating rates from spectral radiative transfer							Y	Y	Y	Y
Feedback of 1909 absorbing gases in explicit mechanism to heating rates from spectral radiative transfer										Y
Feedback of online bulk or modal aerosol to parameterized heating rate				Y						
Feedback of all discrete size-resolved aerosol particles to heating rates from spectral solar and thermal-IR radiative transfer							Y	Y	Y	Y
Feedback of all discrete size-resolved hydrometeor particles to heating rates from spectral solar and thermal-IR radiative transfer								Y	Y	Y
Online feedback of chemically-varying gases or particles back to photolysis to drive photochemistry										
No photolysis				Y						
Photolysis from lookup table or fixed, without feedback	Y	Y			Y					
Feedback of online ozone only to lookup-table photolysis			Y			Y				
Feedback of all gases, including ozone, to online photolysis calculated from spectral radiative transfer							Y	Y	Y	Y
Feedback of all gases in near-explicit mechanism to online photolysis for 2644 photoprocesses calculated from spectral radiative transfer										Y
Feedback of all discrete size-resolved aerosol particles to photolysis							Y	Y	Y	Y

calculated from spectral radiative transfer										
Feedback of all discrete size-resolved hydrometeor particles to photolysis calculated from spectral radiative transfer								Y	Y	Y

Processes / numerical techniques in GATOR-GCMOM

Table 2 below lists most processes and numerical techniques included in GATOR-GCMOM. It also provides the year the first version of the process or technique was added, the first reference for the process in a GATOR 3-D model, and an indication of whether the processes was the first to appear in any three-dimensional model (including, global, regional, high-resolution local, cloud, air quality, meteorological, climate, coupled, nested, community, or research-grade models).

The table indicates that ~450 processes and numerical techniques appeared in GATOR-GCMOM before appearing in any other 3-D model. To date, most of these processes still do not appear in any other model.

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Table 2. Processes and numerical techniques included in GATOR GCMOM. Also shown are the year the first version of the process or technique was added, the first reference for the process in one of the GATOR 3-D models, and an indication of whether the processes was the first to appear in any three-dimensional model (including, global, regional, high-resolution, cloud, air quality, meteorological, coupled, nested, community, or research-grade models). The last column counts the number of processes/techniques first appearing in a GATOR model. Acronyms are listed in a footnote at the end of the table.

	Year first version of coding completed in GATOR models	First Reference in 3-D GATOR models	Was this the first treatment of this process in any 3-D model?	No. of 'Yes'
Original Version of GATOR				
Air quality module	1990	J94c, J96b		

Gas processes				
Emissions from an inventory	1993	J94c, J96b	No	
Gas photochemistry w/ online spectral photolysis affected by DSCRAP	1993	J94a	Yes	1
Gas-to- particle conversion	1991	J94c, J96b	No	
Dry deposition	1990	J94c, J96b	No	
Aerosol processes (discrete size- and composition-resolved)				
Prognostic equations for both aerosol mass and number versus size	1993	J94c, J97a	Yes	2
DSCRAP emissions from an inventory	1993	J94c, J97a	No	
DSCRAP homogeneous nucleation	1991	J94c, J97a	No	
DSCRAP coagulation among multiple size distributions	1993	J94b	Yes	3
DSCRAP condensational growth	1993	J94c, J95a	No	
DSCRAP dissolutional growth	1993	J94c, J95a	Yes	4
DSCRAP reversible chemical equilibrium	1991	J94c, J96a	No	
DSCRAP irreversible aqueous chemistry	1992	J97a	Yes	5
DSCRAP dry deposition / sedimentation	1990	J94c, J97a	No	
Transport processes (gas/DSCRAP horizontal/vertical advection/diffusion)	1990	J94c, J96b	No	
Radiation processes (gas/DSCRAP optics, spectral radiative transfer)	1990	J94c, J96b	Yes	6
Original Limited-Area Dynamics Module (MMTD)				
Limited-area mesoscale dynamics module (MMTD) of L95	1993	J94c, J96b	No	
Pressure, geopotential, air temperature, wind velocity, moisture (L95)	1993	J94c, J96b	No	
Conserves enstrophy in frictionless, barotropic flow limit	1993	J94c, J96b	No	
Conserves total energy for frictionless, adiabatic flow and conserves mass	1993	J94c, J96b	No	
Conserves potential enthalpy for adiabatic flow; hydrostatic	1993	J94c, J96b	No	
Uses Arakawa C-grid	1993	J94c, J96b	No	
Soil temperature, soil moisture, turbulence	1993	J94c, J96b	No	
First Online, Coupled Regional Air Quality-Meteorological Model (GATORM=GATOR-MMTD)				
Online coupling of air quality / limited-area dynamics modules	1993	J94c, J96b	Yes	7
Feedback of all photochemically-active gases, DSCRAP to radiative transfer for heating rates	1993	J94c, J96b	Yes	8
Use of heating rates from all photochemically-active gases and DSCRAP to drive meteorology	1993	J94c, J96b	Yes	9
Transport of all photochemically-active gases/DSCRAP with online modeled winds/turbulence	1993	J94c, J96b	Yes	10
Option to transport gases/DSCRAP with MMTD advection scheme	1996	J97d	Yes	11
Original Global Dynamics Module (UCLA AGCM)				
Global atmospheric general circulation module (UCLA AGCM) of A81	1994	J95c, J00	No	
Pressure, geopotential, air temperature, wind velocity, moisture (A81)	1994	J95c, J00	No	
Conserves potential enstrophy in frictionless, barotropic flow limit	1994	J95c, J00	No	
Conserves total energy for frictionless, adiabatic flow and conserves mass	1994	J95c, J00	No	
Conserves potential enthalpy for adiabatic flow; hydrostatic	1994	J95c, J00	No	
Uses Arakawa C-grid	1994	J95c, J00	No	
Subgrid cumulus liquid and ice clouds from A74	1994	J95c, J00	No	

First Online, Coupled Global Air Quality-Weather-Climate Model (GATORG)				
Online coupling of air quality / global dynamics modules	1993	J95c, J99d, J00	Yes	12
Feedback of all photochemically-active gases, DSCRAP to radiative transfer for heating rates	1994	J95c,J99d,J01c	Yes	13
Use of heating rates from all photochemically-active gases and DSCRAP to drive meteorology	1994	J95c,J99d,J01c	Yes	14
Transport of all photochemically-active gases/DSCRAP with online modeled winds/turbulence	1994	J95c,J99d,J01c	Yes	15
Option to transport gases/DSCRAP with GCM advection scheme	1995	J01c	Yes	16
First Nested, Online, Coupled Global-Through-Urban Scale Model (GATOR-GCMM)				
One-way nesting from global to urban scale	1998	J01c	Yes	17
All gas/aerosol/radiative/surface processes solved in all domains.	1998	J01c	Yes	18
Inflow of gases, DSCRAP, meteorol. parameters at horizontal boundaries	1998	J01c	Yes	19
Optical properties above top of finer domain from coarser domain.	2006	J08a	Yes	20
Any number of nested layers and domains in each layer.	1998	J01c	Yes	21
A nested layer consists of one or more nested domains within the layer that are independent of each other	1998	J01c	Yes	22
Each domain in each layer feeds boundary conditions to any number of domains in the next finer layer of nesting.	1998	J01c	Yes	23
The coarsest layer of nesting is the global scale	1998	J01c	No	
Regardless of number of domains, memory required never exceeds 2.1 times the memory of the largest domain.	1998	J01c	Yes	24
First Online, Coupled Model w/ Discrete Size, Composition-Resolved Clouds (GATOR-GCMOM)				
Online coupling of discrete size- and composition-resolved cloud processes	2000	J02b, J03, J07b	Yes	25
First Coupled Atmosphere-Ocean Model w/ 3-D Explicit Ocean Chemistry (GATOR-GCMOM)				
Online coupling of 2-D ocean dynamics, 3-D ocean chemistry / diffusion	2001	J02b	Yes	26
2-D ocean dynamics	2001	K07, J02b	No	
3-D ocean chemistry and diffusion, ocean/atmosphere exchange	2004	J05c	Yes	27
First-3-D Model to Treat Subgrid Aircraft Exhaust from All Commercial Flights Worldwide				
Online subgrid contrail microphysical growth / dilution / shear	2009	J09b	Yes	28
First 3-D Model to Treat Near-Explicit Photochemistry				
Near-explicit 3-D photochemistry (>13,500 reactions) in GATOR-GCMOM	2009	J09c	Yes	29
Parallelized GATOR-GCMOM				
Parallelization of nested, online coupled GATOR-GCMOM	2001	J04d	Yes	30

Gas, Aerosol, Cloud, Transport, Radiative, Surface, Ocean Processes in GATOR-GCMOM				
Emissions				
Anthropogenic emissions of gases				
Open biomass burning	2000	J02b	No	
CO ₂ , CO, H ₂ O, H ₂ , CH ₄ , NO, NO ₂ , N ₂ O, NH ₃ , SO ₂ , COS, CH ₃ Cl, CH ₃ Br, CH ₃ SCH ₃ , CH ₃ SSCH ₃ , C ₂ H ₆ , C ₂ H ₄ , C ₃ H ₈ , C ₃ H ₆ , C ₄ H ₁₀ , C ₄ H ₈ , C ₄ H ₆ , C ₅ H ₁₂ , C ₅ H ₁₀ , C ₅ H ₈ , C ₆ H ₆ , toluene, monoterpenes, xylene, ethylbenzene, CH ₃ OH, C ₂ H ₅ OH, HCHO, CH ₃ CHO, CH ₃ COCH ₃ , benzaldehyde, HCOOH, CH ₃ COOH	2000	J02b	Yes	31
Biofuel burning separated from other emissions	2003	J04d	Yes	32
Same chemicals as open biomass burning	2003	J04d	Yes	33
Vehicles, power plants, industry, homes, etc.	1993	J96b	No	
Same chemicals as open biomass burning	1993	J96b	Yes	34
Plume rise equation for stack emissions	1993	J96b	No	
Shipping	2000	J02b, J06a	No	
CO ₂ , CO, H ₂ O, H ₂ , CH ₄ , NO, NO ₂ , HONO, N ₂ O, SO ₂ , HSO ₃ , H ₂ SO ₄	2000	J02b, J06a	Yes	35
Aircraft	2005	J07a	No	
CO ₂ , CO, H ₂ O, H ₂ , CH ₄ , NO, NO ₂ , HONO, N ₂ O, SO ₂ , HSO ₃ , H ₂ SO ₄ , speciated NMVOC	2005	J07a	Yes	36
Gas emissions from all individual flights worldwide at subgrid scale	2007	J09b	Yes	37
Natural emissions of gases				
Dimethyl sulfide from phytoplankton	2000	J01b	No	
Vegetation emissions				
Isoprene	1993	J96b	No	
Accounts for temperature, PAR, LAI variation with time	2003	J05f	No	
PAR determined from spectral radiative transfer calculation	2003	J05f	Yes	38
Monoterpenes	2003	J05f	No	
Other volatile organic carbon	2003	J05f	No	
Carbon dioxide from plant respiration	2006	J09a	No	
Soil bacteria respiration				
NO	1996	J05f	No	
H ₂ , N ₂ O, CO ₂	2006	J09a	No	
Carbon dioxide				
Plant cellular respiration / photosynthesis	2006	J09a	No	
Phytoplankton respiration / photosynthesis	2008	J09b	No	
Soil bacteria respiration	2006	J09a	No	
Ocean evaporation (see ocean-atmosphere exchange)	2004	J05c	No	
Lightning, hot channel and corona discharge				
NO, NO ₂ , HONO, N ₂ O, HNO ₃ , CO, H ₂ O ₂ , HO ₂	2000	J02b, J09a	Yes	39
Lightning strokes calculated from bounceoff rate following discrete size-resolved liquid-ice, liquid-graupel, ice-graupel, liquid, liquid, ice-ice, and graupel-graupel collisions.	2000	J02b, J09a	Yes	40
Volcanos, sporadic and continuous				
H ₂ O, CO ₂ , CO, H ₂ , SO ₂ , H ₂ S, CS ₂ , OCS, HCl, HBr, HF	2000	J02b	Yes	41
Ocean biological production of CH ₄ , H ₂ , N ₂ O	2006	J09a	No	
Anthropogenic DSCRAP emissions				

Open biomass burning	2000	J01b, J02b	No	
BC, POM, H ₂ O(l), NH ₄ ⁺ , Na ⁺ , K ⁺ , Mg ²⁺ , Ca ²⁺ , H ⁺ , H ₂ SO ₄ (aq), HSO ₄ ⁻ , SO ₄ ²⁻ , Cl ⁻ , Br ⁻ , NO ₃ ⁻ , HCO ₃ ⁻	2000	J01b, J02b	Yes	42
Biofuel burning, separated from other emissions	2003	J04d	Yes	43
Same chemicals as open biomass burning	2003	J04d	Yes	44
Vehicles, power plants, industry, homes, etc.	1993	J97b	No	
Same chemicals as open biomass burning	1993	J97b	Yes	45
Plume rise equation for stack emissions	1993	J96b	No	
Spatial emissions of explicit species for near-explicit photochemistry	2009	J09c	Yes	46
Shipping	2000	J02b, J06a	No	
BC, POM	2000	J02b, J06a	No	
Aircraft	2005	J07a	No	
BC, POM, H ⁺ , H ₂ SO ₄ (aq), HSO ₄ ⁻ , SO ₄ ²⁻	2005	J07a	Yes	47
Emissions from all individual commercial aircraft worldwide	2007	J09b	Yes	48
Each individual contrail tracked as a subgrid tube in each grid cell	2007	J09b	Yes	49
Contrails form by deposition aircraft H ₂ O onto DSCRAP emission	2007	J09b	Yes	50
Contrail ice crystals grow by collision-coalescence/H ₂ O deposition	2007	J09b	Yes	51
Contrail plumes spread by subgrid dilution from parameterization	2007	J09b	Yes	52
Contrails sublimated upon sufficient dilution	2007	J09b	Yes	53
Contrail merges with grid-scale material upon dilution to grid scale ₂	2007	J09b	Yes	54
Road dust	1993	J97b	No	
BC, POM, NH ₄ ⁺ , Na ⁺ , K ⁺ , Mg ²⁺ , Ca ²⁺ , H ⁺ , H ₂ SO ₄ (aq), HSO ₄ ⁻ , SO ₄ ²⁻ , Cl ⁻ , NO ₃ ⁻ , Fe, Al, Si	2004		Yes	55
Natural DSCRAP emissions				
Sea spray and spume drops	1994	J97b	No	
H ₂ O(aq), Na ⁺ , K ⁺ , Mg ²⁺ , Ca ²⁺ , H ⁺ , H ₂ SO ₄ (aq), HSO ₄ ⁻ , SO ₄ ²⁻ , Cl ⁻ , Br ⁻ , NO ₃ ⁻ , HCO ₃ ⁻ , POM	1994	J97b	Yes	56
Function of wind speed	1994	J97b	No	
Use modeled seawater composition (see ocean equilibrium chem..)	2007	J09a	Yes	57
Soil dust	2000	J01b	No	
Na ⁺ , K ⁺ , Mg ²⁺ , Ca ²⁺ , SiO ₂ (s), Fe ₂ O ₃ (s), Al ₂ O ₃ (s)	2000	J01b	Yes	58
Function of wind speed	2000	J01b	No	
Function of subgrid soil class, each with diff. composition	2000	J01b	Yes	59
Pollen	2005	J09a	Yes	60
Fungal spores	2005	J09a	Yes	61
Bacteria from soils	2005	J09a	Yes	62
Bacteria from the ocean	2005	J09a	Yes	63
Volcanos, sporadic and continuous	2000	J02b	No	
SO ₄ ²⁻ , Na ⁺ , K ⁺ , Ca ²⁺ , Fe, Al, Zn	2000	J02b	Yes	64
Gas photochemistry				
Fully-coupled online tropospheric chemistry-radiation-meteorology	1993	J94c, J96b	Yes	65
Near-explicit photochemistry solved in 3-D coupled model	2009	J09c	Yes	66
All absorbing gases from online spectral photochemistry feed back to dynamics through spectral heating rates	1993	J94c, J96b	Yes	67
All gases solved during photochemistry are transported in 3-D	1993	J94c, J96b	Yes	68
All gases involved in photochemistry are solved with time-dependent exact solution (no steady state or approximations)	1993	J94c, J96b	Yes	69
Fully-coupled online global trop/strat. chemistry-radiation-meteorology	1994	J95c, J01c	Yes	70
All absorbing gases, including ozone, from online spectral photochemistry feed back to dynamics through spectral heating rates	1994	J95c, J01c	Yes	71

All absorbing gases from near-explicit mechanism feed back to dynamics through spectral heating rates	2009	J09c	Yes	72
All gases solved during photochemistry are transported in 3-D	1994	J95c, J01c	Yes	73
All gases in near-explicit mechanism are transported in 3-D	2009	J09c	Yes	74
All gases involved in photochemistry are solved with time-dependent exact solution (no steady state or approximations).	1994	J95c, J01c	Yes	75
All gases in near-explicit mechanism solved with exact solution	2009	J09c	Yes	76
Photochemistry produces inorganic and organic gases used for size-resolved aerosol growth in coupled gas-aerosol-meteorological model	1994	J97a	Yes	77
Development of method of converting pseudo-first-order to second-order rate coefficients to ensure mass conservation of heterogeneous reactions	2006	J08c	Yes	78
Family chemistry solution scheme	1990	J94c, J99d	No	
Matrix inversion to solve for species concentrations in family	1990	J94c, J99d	Yes	79
Multistep implicit-explicit (MIE) solution scheme	1992	J94a	Yes	80
Iterated forward and backward Euler converge to each other	1992	J94a	Yes	81
SMVGEAR / SMVGEAR II	1993	J94a, J98a	Yes	82
Near-exact solution to first-order ODEs, based on Gear's method	1993	J94a	Yes	83
Predicts the time step (10^{-10} to 900 s)	1993	J94a	Yes	84
Predicts the order of convergence (1^{st} to 5^{th})	1993	J94a	Yes	85
Uses a variable relative error tolerance (default is 10^{-3})	1993	J94a	Yes	86
Uses a variable absolute error tolerance	1993	J94a	Yes	87
Predicted absolute error tolerance (SMVGEAR II)	1997	J98a	Yes	88
Sparse matrix techniques				
Species with fewest partial derivative terms at top of matrix	1993	J94a	Yes	89
Eliminate matrix decomposition/backsubstitution multiplies by zero	1993	J94a	Yes	90
Compress matrix arrays to minimize memory	1993	J94a	Yes	91
Separate matrices for day/night chemistry	1993	J94a	Yes	92
Division of grid domain into blocks of grid cells	1993	J94a	Yes	93
Vectorization around the grid cell dimension in each block	1993	J94a	Yes	94
Minimizes array references on vector and scalar machines	1993	J94a	Yes	95
Speeds array operations on vector machines	1993	J94a	Yes	96
Less memory than vectorization around full domain.	1993	J94a	Yes	97
Reordering of grid cells among all blocks by stiffness	1994	J95b	Yes	98
Allows stiff cells and nonstiff cells to be solved together	1994	J95b	Yes	99
Division of domain into grid blocks used parallelization	2001	J94a	Yes	100
Different sets of chemistry for different regions of atmosphere	1994	J95b	Yes	101
First derivatives, partial derivatives, matrices automatically generated from a changeable input species and reaction rate set.	1993	J94a	Yes	102
Photolysis coefficients updated each SMVGEAR time step	1993	J94a	Yes	103
Interpolated between coefficients calculated from spectral radiative transfer at the begin and end of each chemistry time interval	1993	J94a	Yes	104
Discrete size- and composition-resolved aerosol processes				
Characteristics of aerosol size distributions				
Any number of aerosol size distributions	1991	J94b	Yes	105
Any number of discrete size bins per aerosol distribution	1991	J94b	No	
Any number of chemical components per size bin per distribution	1991	J94b	No	
Predicts number concentration of each bin of each distribution	1991	J94b	Yes	106
Predicts mole conc. of each chem. in each bin of each distribution	1991	J94b	Yes	107

Single-particle volume consists of solution + nonsolution component	1998	J02a	Yes	108
Solution density determined from densities of electrolytes	1998	J02a	Yes	109
Aerosol size structures (how size distributions vary in time)				
Hybrid	1993	J95a	Yes	110
Constant core volume but variable shell volume	1993	J95a	Yes	111
Moving center	1994	J97a	Yes	112
Particles moved when larger/smaller than bin boundaries	1994	J97a	Yes	113
Full moving	1993	J95a	N/A	
Particles moved to their exact volumes. (0-D only)	1993	J95a	N/A	
Quasistationary	1994	J97a	Yes	114
Number/volume partitioned between adjacent bins	1994	J97a	Yes	115
Nucleation				
Homogeneous homomolecular and binary nucleation	1991	J94c, J97a	No	
Homogeneous ternary nucleation	2003	J06a	Yes	116
Heterogeneous homomolecular and binary nucleation	1991	J99d, J05d	No	
Nucleation solved simultaneously with condensation	1993	J02a	Yes	117
Aerosol-aerosol coagulation				
COAGSOLV noniterative solver for discrete size distributions	1993	J94b	Yes	118
Positive-definite, unconditionally stable for any time step	1993	J94b	Yes	119
Conserves single-particle volume of total particle, all components	1993	J94b	Yes	120
Conserves volume concentration of total particle, all components	1993	J94b	Yes	121
Solves equations for any volume ratio of adjacent size bins > 1	1993	J94b	Yes	122
Solves any number externally-, one internally-mixed distribution	1993	J94b	Yes	123
Solves any number externally- and internally-mixed distributions	2000	J01b, J02a	Yes	124
Solves for particle number of all sizes of all distributions	1993	J94b	Yes	125
Solves for all individual components of all sizes of all distributions	1993	J94b	Yes	126
Discrete size-resolved aerosol-aerosol coagulation kernels over time	1993	J94b	Yes	127
Brownian diffusion	1993	J94b	Yes	128
Brownian diffusion enhancement	1993	J94b	Yes	129
Turbulent shear	1993	J94b	Yes	130
Turbulent inertial motion	1993	J94b	Yes	131
Gravitational settling	1993	J94b	Yes	132
Van der Waals forces	2003	J04a	Yes	133
Viscous forces	2003	J04a	Yes	134
Fractal geometry	2003	J04a	Yes	135
Equilibrium chemistry within aerosols and between gases/aerosols				
Coupling size-resolved equilibrium with dissolutional growth in 3-D	1991	J96a	Yes	136
Aerosol equilibrium for vapor pressures within all DSCRAP in all size distributions	1991	J96a	Yes	137
Vapor pressures for nonequilibrium dissolutional growth	1991	J96a	Yes	138
Internal aerosol equilibrium for composition after growth	1991	J96a	Yes	139
Equilibrium between gases and all DSCRAP in 3-D model	1991	J96a	No	
EQUISOLV chemical equilibrium solver	1991	J96a	Yes	140
Solves any number equations among gases, ions, liquids, solids	1991	J96a	Yes	141
e.g., H ₂ O(l), H ₂ SO ₄ (aq), HSO ₄ ⁻ , SO ₄ ²⁻ , NO ₃ ⁻ , Cl ⁻ , H ⁺ , NH ₄ ⁺ , Na ⁺	1991	J96a	Yes	142
Solid formation depends on deliquescence and crystallization RHs, and whether RH is increasing or decreasing	1991	J96a	Yes	143
Determines aerosol pH, liquid water content and composition	1991	J96a	Yes	144

Uptake of water reduces the relative humidity iteratively, feeding back to water uptake and aerosol composition	2002	J08a	Yes	145
Uptake of water warms air temperature iteratively	2002	J08a	Yes	146
Numerical solution iterative around all equations	1991	J96a	Yes	147
Unconditionally stable, positive definite, conserves moles, charge	1991	J96a	Yes	148
Individual equations solved with MFI method	1991	J96a	Yes	149
Iterative, exact solution to individual equations	1991	J96a	Yes	150
Water content in all bins of all distributions from ZSR method	1991	J96a	No	
Mixed electrolyte solute activity coefs. from Bromley's method	1991	J96a	No	
Temperature dependence of solute activity coefficients	1991	J96a	Yes	151
EQUISOLV II chemical equilibrium solver	1997	J99c	Yes	152
Solves any number equations among gases, ions, liquids, solids	1997	J99c	Yes	153
e.g., H ₂ O(l), H ₂ SO ₄ (aq), HSO ₄ ⁻ , SO ₄ ²⁻ , HNO ₃ (aq), NO ₃ ⁻ , Cl ⁻ , H ₂ CO ₃ (aq), HCO ₃ ⁻ , CO ₃ ²⁻ , H ⁺ , NH ₄ ⁺ , Na ⁺ , Mg ²⁺ , Ca ²⁺ , K ⁺	1997	J99c	Yes	154
e.g., 25 or more solid electrolytes can form	1997	J99c	Yes	155
Solution iterative around all equations,	1997	J99c	Yes	156
Unconditionally stable, positive definite, conserves moles, charge	1997	J99c	Yes	157
Individual equations solved with AEI method	1997	J99c	Yes	158
Exact analytical solution to individual equations	1997	J99c	Yes	159
Dissolutional growth/evaporation between gases/DSCRAP				
Dissolution of inorganic gases into DSCRAP	1993	J95a	Yes	160
Dissolution of organic gases into DSCRAP	1994	J97a, J04d	Yes	161
Dissolution into multiple aerosol distributions simultaneously	1998	J02a	Yes	162
SMVGEAR solution to dissolution	1993	J96a	Yes	163
Exact solution	1993	J96a	Yes	164
Conserves moles between gas and all particle size bins	1993	J96a	Yes	165
Effective Henry's constants/vapor pressures from EQUISOLV	1993	J96a	Yes	166
APD solution to dissolution	1993	J97c	Yes	167
Noniterative, analytical solution to discretized equation	1993	J97c	Yes	168
Unconditionally-stable, positive definite	1993	J97c	Yes	169
Conserves moles between gas and all particle size bins	1993	J97c	Yes	170
Effective Henry's constants/vapor pressures from EQUISOLV	1993	J97c	Yes	171
APNCD solution	1998	J02a	Yes	172
Solves nucleation, condensation, dissolution together	1998	J02a	Yes	173
Solves equations between gas and multiple size distributions	1998	J02a	Yes	174
Allows condensation in some bins, dissolution in others	1998	J02a	Yes	175
Noniterative, unconditionally stable, positive definite	1998	J02a	Yes	176
Conserves moles between gas and all bins in all distributions	1998	J02a	Yes	177
Effective Henry's constants/vapor pressures from EQUISOLV II	1998	J02a	Yes	178
PNG-EQUISOLV II solution	2003	J05a	Yes	179
Couples dissolution growth/equilibrium at long time step	2003	J05a	Yes	180
Dissolution of semivolatile acid gases at high/moderate LWC	2003	J05a	Yes	181
pH, aerosol comp. for effective Henry's const. from EQUISOLV II	2003	J05a	Yes	182
Condensation of semivolatile acid gases at low LWC	2003	J05a	Yes	183
Vapor pressure determined over solids from analytical solution	2003	J05a	Yes	184
Vapor pressure determined over liquids from EQUISOLV II	2003	J05a	Yes	185
Condensation involatile gases at all LWC	2003	J05a	Yes	186
Equilibration NH ₃ /NH ₄ ⁺ and pH between gas/all distributions	2003	J05a	Yes	187
Equilibration of internal-aerosol liquid, ion, solids, pH, LWC	2003	J05a	Yes	188
Conserves moles/charge between gas and all size distributions	2003	J05a	Yes	189

Solution method stable, nonoscillatory at long time step	2003	J05a	Yes	190
Condensation/evaporation of gases onto/from DSCRAP				
Condensation of inorganic gases onto DSCRAP	1993	J94c, J95a	No	
Condensation of organic gases onto DSCRAP	1996	J98b, J04d	No	
Condensation onto multiple aerosol distributions simultaneously	1998	J02a	Yes	191
Terms in discrete size-resolved growth equations in 3-D				
Diffusion, collision geometry, sticking probability, ventilation	1991	J95a	No	
Kelvin effect term	1991	J95a	No	
Raoult's law term	2004	J05e	Yes	192
Radiative cooling effect term	1991	J95a	Yes	193
SMVGEAR solution	1993	J95a	Yes	194
Exact solution to condensation/evaporation	1993	J95a	Yes	195
Conserves moles between gas and all aerosol size bins	1993	J95a	Yes	196
APC solution	1993	J97c	Yes	197
Noniterative, analytical solution to discretized equation	1993	J97c	Yes	198
Unconditionally-stable, positive definite	1993	J97c	Yes	199
Conserves moles between gas and all aerosol size bins	1993	J97c	Yes	200
APNCD solution	1998	J02a	Yes	201
Solves nucleation, condensation, dissolution together	1998	J02a	Yes	202
Solves equations between gas and multiple size distributions	1998	J02a	Yes	203
Noniterative, unconditionally stable, positive definite	1998	J02a	Yes	204
Conserves moles between gas and all bins in all distributions	1998	J02a	Yes	205
Aqueous chemistry (irreversible)				
Solved within DSCRAP, operator split from gas-aerosol transfer	1992	J97a	Yes	206
Solved together with gas-aerosol transfer to all discrete size bins	1997	J99d, J05d	Yes	207
Gas transfer/chemistry of families solved with SMVGEAR	1997	J99d, J05d	Yes	208
Families partitioned to ions with EQUISOLV	1997	J99d, J05d	Yes	209
Gas transfer/chemistry to liquid aerosol/hydrometeor particles together	2000	J02b, J03	Yes	210
Cloud processes				
Cloud thermodynamics				
Unresolved scales (subgrid clouds)				
AS cumulus parameterization of A74; multiple subgrid clouds	1994	J01c	No	
Clouds form vertically and dissipate at the end of time interval.	1994	J01c	No	
Clouds are formed in equilibrium (thus not time dependent)	1994	J01c	No	
Feedback of momentum, heating, vapor to large scale	1994	J01c	No	
Modified AS scheme of D98	1996	J01c	No	
Similar to AS, but subgrid cloud bases can be above ABL	1996	J01c	No	
Up to 500 subgrid clouds can form per column (1-10 usually do)	1996	J01c	No	
Stratus cloud fraction, LWC from parameterization of M82	2000	J02b	No	
Coupled to turbulence parameterization of M82	2000	J02b	No	
Resolved scales (grid-scale clouds)				
Grid-scale cloud thermodynamics	2005	J07b	No	
Clouds form and move in 3-D over time (thus are time dependent)	2005	J07b	No	
Updrafts can be tilted	2005	J07b	No	
Transport of gases, aerosols, hydrometeors within clouds				
Unresolved scales (subgrid clouds)				
DSCRHP and inclusions transported vertically in time interval	2000	J02b, J03	Yes	211

All chemicals in all sizes in all HP size distributions transported	2000	J02b, J03	Yes	212
HP number concentration in each bin transported as well	2000	J02b, J03	Yes	213
Gas, interstitial DSCRAP are transported consistently	2000	J02b, J03	Yes	214
Convective plume module transported gases, DSCRAP, DSCRHP	2000	J02b, J03	Yes	215
Conserves moles / number exactly	2000	J02b, J03	Yes	216
Turbulent diffusion scheme transports gases, DSCRAP, DSCRHP	2004	J07d	Yes	217
Conserves moles and constant mixing ratio exactly	2004	J07d	Yes	218
Resolved scales (grid-scale clouds)				
DSCRHP and inclusions are transported in 3-D over time	2005	J07b	Yes	219
All chemicals in all DSCRHP size distributions are transported	2005	J07b	Yes	220
DSCRHP number concentration in each bin transported as well	2005	J07b	Yes	221
Modeled grid-scale velocities used to transport material	2005	J07b	No	
Same advection/diffusion solvers as to transport gases, DSCRAP	2005	J07b	Yes	222
Discrete size/composition-resolved cloud microphysics (all scales)				
Microphysical processes are time-dependent and explicit	2000	J02b, J03	No	
Hydrometeor particles are discretely size/composition resolved	2000	J02b, J03	Yes	223
Three hydrometeor distributions can form: liquid, ice, graupel	2000	J02b, J03	No	
DSCRHP form on top of any number of discrete aerosol distributions	2000	J02b, J03	Yes	224
Large particles in each hyd. distribution fall as rain, snow, or hail	2000	J02b, J03	No	
Any number of discrete size bins per hydrometeor distribution	2000	J02b, J03	No	
Any number of chemical inclusions per size bin per hyd. distribution	2000	J02b, J03	Yes	225
Model predicts number concentration of each bin of each hyd. dist.	2000	J02b, J03	No	
Model predicts mole conc. of each chem. in each bin of each hyd. dist.	2000	J02b, J03	Yes	226
Model predicts liquid or ice content of each bin of each hyd. dist.	2000	J02b, J03	No	
Energy/moisture changes due to microphysics feed back to dynamics	2000	J02b, J03	No	
Optical properties of DSCRHP feed back to spectral radiative transfer	2000	J02b, J03	Yes	227
All microphysical processes conserve water vapor, size-resolved aerosol and hydrometeor, precipitation, ground, and ocean water	2000	J02b, J03	Yes	228
All microphysical processes conserve energy	2000	J02b, J03	No	
In-cloud condensation/deposition/evap./subl. (nucleation scavenging)				
DSCRHP grow on multiple aerosol size distributions	2000	J02b, J03	Yes	229
Allows for dual peaks in cloud size distributions	2000	J02b, J03	Yes	230
Aerosol surface tension, composition vary with size/distribution	2000	J02b, J03	Yes	231
Surface tension is function of organic, inorganic composition	2000	J02b, J03	Yes	232
Activated CCN/IDN size bins are determined from the Kohler equation applied to each aerosol size distribution	2000	J02b, J03	Yes	233
Growth results in discrete liquid, ice, or both size distributions	2000	J02b, J03	Yes	234
DSCRHP contain inclusions of all aerosol components they form on	2000	J02b, J03	Yes	235
Solution to hydrometeor growth is extension of APC scheme	2000	J03, J07b	Yes	236
Water vapor competes between liquid and ice during growth onto CCN and IDN aerosol distributions	2000	J03	Yes	237
Water vapor competes among liquid CCN aerosol, ice IDN aerosol, and pre-existing liquid, ice, graupel hyd. distrib. during growth	2000	J07b	Yes	238
Noniterative, unconditionally-stable, positive definite	2000	J03	Yes	239
Conserves moles between gas and all bins of all distributions	2000	J03	Yes	240
Hydrometeor growth solved over quasistationary size structure	2000	J02b, J03	Yes	241
Hydrometeor-hydrometeor coagulation (collision/coalescence)				

Discrete size-resolved coagulation among all hyd. distributions	2000	J02b, J03	No	
Liq.-liq., liq.-ice, liq.-graup., ice-ice, ice-graup., graupel-graupel	2000	J02b, J03	No	
Inclusions in each size of each distribution coagulated as well	2000	J02b, J03	Yes	242
Coagulation produces size-resolved precipitation (rain, snow, hail)	2000	J02b, J03	No	
Size-resolved precipitation particles contain inclusions of underlying CCN/IDN	2000	J02b, J03	Yes	243
COAGSOLV used to solve hyd.-hyd. coagulation	2000	J02b, J03	Yes	244
Noniterative, pos.-definite, uncondit. stable for any time step	2000	J02b, J03	Yes	245
Conserves single-part. volume of total particle, all components	2000	J02b, J03	Yes	246
Conserves volume concentration of total particle, all components	2000	J02b, J03	Yes	247
Solves equations for any volume ratio of adjacent size bins > 1	2000	J02b, J03	Yes	248
Solves for particle number and component concentration	2000	J02b, J03	Yes	249
Components in each distribution coagulate with all distributions	2000	J02b, J03	Yes	250
Lightning formation (see natural emissions of gases)	2000	J05d, J09a	Yes	251
Discrete size-resolved hydromet.-hydromet. coag. kernels over time	1993	J94b	Yes	252
Brownian diffusion	1993	J94b	Yes	253
Brownian diffusion enhancement	1993	J94b	Yes	254
Turbulent shear	1993	J94b	Yes	255
Turbulent inertial motion	1993	J94b	Yes	256
Gravitational settling	1993	J94b	No	
Diffusiophoresis	2000	J02b, J03	Yes	257
Thermophoresis	2000	J02b, J03	Yes	258
Electric charge	2000	J02b, J03	Yes	259
Aerosol-hydrometeor coagulation (aerosol washout)				
Coag. between interstitial aerosol distrib. and hydrometeor distrib.	2000	J03	Yes	260
Size- and distrib.-resolved aer.-liquid, aer.-ice, aer.-graupel coag.	2000	J03	Yes	261
DSCRAP and components coag. to DSCRHP distributions	2000	J03	Yes	262
COAGSOLV used (same as for hydrometeor-hydrometeor coag.)	2000	J02a	Yes	263
Components in each distribution coagulate with all distributions	2000	J03	Yes	264
Coagulated aerosol components incorporated into DSCRHP	2000	J03	Yes	265
Coagulation kernels (same as for hydrometeor-hydrometeor coag.)	1993	J94b, J03	Yes	266
Large liquid drop breakup				
Fragments and chemical inclusions partitioned to smaller size bins	2000	J03	Yes	267
Below-cloud evaporation/sublimation				
Iterative equation for drop surface temperature	2000	J03	Yes	268
Evaporation rate a function of drop surface temperature, size	2000	J03	Yes	269
Complete evaporation/sublimation, release of aerosol cores to air				
Evaporation/sublimation of all water releases DSCRAP to air	2000	J03	Yes	270
DSCRAP released back to mixed aerosol distrib.	2000	J03	Yes	271
Gas washout (dissolution of gases in precipitation)				
Gas dissolution/evap. in liquid precip. solved in vertical column	2000	J03	Yes	272
Supersaturation of gas in drops results in release to gas phase	2000	J03	Yes	273
Undersaturation of gas results in uptake of gas by precip.	2000	J03	Yes	274
Solution conserves moles between gas/precipitation	2000	J03	Yes	275
Irreversible aqueous chemistry in clouds				

Gas transfer / bulk aqueous chemistry solved with SMVGEAR	2000	J02b, J03	Yes	276
Gas transfer/chemistry to liquid aerosol/hydromet. particles together	2000	J02b, J03	Yes	277
Aqueous chemical products redistributed to discrete aerosol and hydrometeor sizes based on initial aer/hyd composition	2000	J02b, J03	Yes	278
Size-resolved aqueous chemistry in clouds with SMVGEAR	2000	J97a	Yes	279
Hydrometeor settling				
Hydrometeor fall speed function of size, density, air viscosity	2000	J03	Yes	280
Precipitation to ground				
Precipitation of size-resolved liquid increases soil water, runoff	1999	J01c	Yes	281
Precipitation of size-resolved ice, graupel increases snow depth	1999	J01c	Yes	282
Precipitation releases size-resolved aerosol inclusions to sea ice, snow	2000	J04d	Yes	283
In- or below-cloud liquid drop freezing				
Heterogeneous-homogeneous freezing				
Freezing rate a function of liquid drop size, temperature, time	2000	J03	No	
Freezing moves liquid hydrometeor particles and their inclusions to graupel distribution	2000	J03	Yes	284
Contact freezing				
Size-resolved coagulation of DSCRAP with liquid HP initiates freezing at subfreezing temperatures.	2000	J03	Yes	285
Solved with COAGSOLV	2000	J03	Yes	286
Freezing moves liquid HP and inclusions to graupel distribution	2000	J03	Yes	287
Evaporative freezing				
Below-cloud evaporation cools drop surface	2000	J03	Yes	288
Evaporation a function of drop surface temperature, size	2000	J03	Yes	289
Lower temperature enhances het./homogeneous freezing rate	2000	J03	Yes	290
Freezing moves liquid HP and inclusions to graupel distribution	2000	J03	Yes	291
Melting of ice and graupel				
Melting rate a function of temperature, evaporation rate, conductivity, ice crystal and graupel size	2000	J03	No	
Evaporation retards melting	2000	J03	Yes	292
Horizontal/vertical advection/diffusion				
All photochemically-active gases are transported in 3-D	1993	J94c, J96b	Yes	293
Winds/diffusion coefficients for advection/diffusion of gases, particles predicted by online dynamics module	1993	J94c, J96b	Yes	294
Region/global advec./diffusion w/ 4 th -order finite element scheme of T89	1990	J94c, J96b	Yes	295
Used for all gases, AP, AP components of all sizes of all distributions	1990	J94c, J96b	Yes	296
Regional advection/diffusion w/ 2 nd -order finite difference scheme used to transport water vapor, energy in MMTD	1996	J97d	Yes	297
Used for all gases, AP, AP components of all sizes of all distributions	1990	J96b	Yes	298
Change in air density during advection exactly consistent with change in air density from regional dynamics module	1990	J96b	Yes	299
Global advection w/ 13-point, 4 th -order scheme of A95 used to transport water vapor energy in global dynamics module.	1995	J01c	Yes	300
Used for all gases, AP, AP components of all sizes of all distributions	1995	J01c	Yes	301
Change in air density during advection exactly consistent with change in	1995	J01c	Yes	302

air density from global dynamics module				
Global/regional advection/diffusion w/ positive-definite, monotonic, nonoscillatory scheme of W98/W00	1998	J01c	Yes	303
Used for all gases, AP, AP components of all sizes of all distributions	1998	J01c	Yes	304
Used for all HP and inclusions when clouds resolved	2005	J07b	Yes	305
Vertical diffusion operator split from advection				
Unconditionally stable 2 nd -order solution to diffusion	2004	J07d	No	
Scheme conserves moles/number and constant mixing ratio exactly	2004	J07d	?	
Used for all gases, DSCRAP and components in all size distributions	2004	J07d	Yes	306
Used for all DSCRHP and inclusions in air when clouds are not resolved	2005	J07d	Yes	307
Used for all DSCRHP and inclusions in clouds when clouds are resolved	2005	J07d	Yes	308
Used for vertical diffusion all ocean chemicals	2004	J05c	Yes	309
Turbulent diffusion coefficients for momentum/energy				
Calculated from online resolved winds, temperatures, moisture	1993	J96b	No	
Turbulent diffusion coefficients for gases limited by molecular diffusion	1993	J96b	No	
Turbulent diffusion coefficients for DSCRAP and DSCRHP include Brownian diffusion coefficient versus particle size	2004	J05e	Yes	310
Hybrid scheme of L95				
Regional scales	1993	J96b	No	
Global scale	1994	J01c	Yes	311
2.5-order prognostic equations for TKE of M82				
Accounts for feedback of stratus clouds to turbulence	2000	J02b	No	
Regional scales	2000	J04b	No	
Global scale	2000	J02b	No	
Dry / wet removal of gases, aerosol particles, hydrometeor particles				
Dry deposition of gases				
Deposition equations solved together with emissions	1990	J94c, J96b	No	
Resistance approach	1993	J94c, J96b	No	
Surface resistance over land based on landuse type	1997	J99d, J01c	No	
At water-air interfaces, gas-water transfer equations solved	2004	J05c	Yes	312
Wet deposition of gases				
All gases dissolve in/evaporate from liquid precip. (see gas washout)	2000	J03	Yes	313
Dry deposition of DSCRAP				
Deposition equations solved together with emiss./sedimentation	1990	J94c, J97a	No	
Resistance approach	1993	J97a, J99d	No	
Sedimentation of DSCRAP				
Sedimentation equations solved together with emissions/dry dep.	1990	J94c, J97a	No	
Resistance approach	1993	J97a, J99d	No	
Wet deposition of DSCRAP				
DSCRAP enter DSCRHP by nucleation scavenging and aerosol washout. Precipitation particles that fall to the ground contain DSCRAP (see nucleation scavenging and aerosol washout)	2000	J03	Yes	314
Wet deposition of DSCRHP (see Precipitation to ground)				

Spectral radiative transfer				
Online spectral UV/Visible radiative transfer for actinic fluxes/photolysis	1991	J94c, J96b	Yes	315
Use of spectral two-stream code of T89	1991	J94c, J96b	Yes	316
Feedback of time-varying gases to spectral radiative transfer for photolysis in online coupled air quality-meteorological model	1993	J94c, J96b	Yes	317
Feedback of time-varying DSCRAP to spectral radiative transfer for photolysis in an online coupled air quality-meteorological model	1993	J94c, J97b	Yes	318
Feedback of DSCRAP to ozone through photolysis in an online coupled 3-D air quality-meteorological model.	1993	J97b, J98b	Yes	319
Currently 84 UV and visible wavelengths for photolysis	2001	J04d, J05b	Yes	320
Online spectral radiative transfer for visibility in 3-D	1992	J94c	Yes	321
Online spectral radiative transfer for PAR in 3-D	2003	J05f	Yes	322
Online spectral (rather than broadband) UV/Vis/NIR/TIR radiative transfer for heating rates	1993	J94c, J96b	Yes	323
Use of spectral two-stream code of T89	1991	J94c, J96b	Yes	324
Feedback of time-varying gases to spectral radiative transfer for heating rates in online coupled air quality-meteorological model	1993	J94c, J96b	Yes	325
Feedback of time-varying DSCRAP to spectral radiative transfer for heating rates in online coupled air quality-meteorological model	1993	J94c, J97b	Yes	326
Feedback of time-varying DSCRAP to temperatures in an online coupled 3-D air quality-meteorological model	1993	J97b, J98b	Yes	327
Feedback of time-varying DSCRAP to winds through heating rates in an online coupled 3-D air quality-meteorological model	1993	J97b, J06b	Yes	328
Currently 676 wavelengths/probability intervals for heating rates	2001	J04d, J05b	Yes	329
84 UV and visible wavelengths	2001	J04d, J05b	Yes	330
224 NIR (28 wavelengths, each with 8 probability intervals)	2001	J04d, J05b	Yes	331
368 TIR (46 wavelengths, each with 8 probability intervals)	2001	J04d, J05b	Yes	332
Spectral optical properties of DSCRAP				
Spectral optical properties of all aerosol particles of all sizes in multiple size distributions.	1991	J94c, J97a, J02a	Yes	333
Spectral forward, total scattering/absorption efficiencies vs. size	1991	J94c, J97a, b	Yes	334
Mie solver for stratified spheres of T81 used	1991	J97a, b	Yes	335
Single particles in each size bin divided into core and shell in 3-D	1994	J97a	Yes	336
BC core / mixed shell	1994	J97a, J99b	Yes	337
Mixed core / ammonium nitrate shell	1997	J99b	Yes	338
Shells divided into solution/nonsolution components	2000	J02	Yes	339
Solution refractive indices from partial molar refraction theory	2000	J02	Yes	340
Size-resolved shells or cores include spectral UV/Visible absorption by				
Black carbon (BC)	1994	J97a, J99b	Yes	341
Ammonium nitrate	1997	J99b	Yes	342
Nitrated aromatic aerosols	1997	J99b	Yes	343
Benzaldehydes	1997	J99b	Yes	344
Benzoic acids	1997	J99b	Yes	345
Aromatic polycarboxylic acids	1997	J99b	Yes	346
Phenols,	1997	J99b	Yes	347
Polycyclic aromatic hydrocarbons (PAHs)	1997	J99b	Yes	348
Organic bases	1997	J99b	Yes	349
Iron oxide	1998	J01a	Yes	350
Aluminum oxide	1998	J01a	Yes	351

Spectral optical properties of bulk hydrometeor particles				
Liquid water/ice from cumulus/stratus parameterization	1994	J01a, J01b	No	
Assume modified gamma distribution to determine size segregation	1994	J01a, J01b	No	
Spectral optical props. account for discrete liquid/ice HP sizes in 3-D	1994	J01a, J01b	Yes	352
Spectral optical properties of discrete size-resolved HP (DSCRHP)				
Accounts for liquid, ice, and graupel discrete size distributions	2000	J02b, J03	Yes	353
Optical calculation assume either				
Pure water, ice, or graupel in each bin	2000	J02b, J03	Yes	354
BC core; water, ice, or graupel shell (core/shell) in each bin	2004	J06a	Yes	355
Multiple BC inclusions (DEMA) in each bin	2004	J06a	Yes	356
Ice crystals/graupel approximated as collection of spheres of equivalent volume:area ratio and total volume for Mie calculations	2004	J05f	Yes	357
Spectral optical properties of scattering gases (Rayleigh scattering)				
	1990	J94c, J96b	No	
Spectral optical properties of all absorbing / photolyzing gases				
Spectral opt. props of all absorbing/photolyzing gases treated online	1991	J94c, J96b	Yes	358
UV/Visible gas absorption				
Spectral absorption cross sections of all photolyzing gases for heating	1990	J94c, J96b	Yes	359
Temperature-dependence of absorption cross sections for heating	1993	J94c, J96b	Yes	360
Spectral UV/visible absorption by nitrated aromatic gases	1997	J99a	Yes	361
Spectral quantum yields of all photolysis processes	1990	J94c, J96b	No	
For use in coupled air quality-meteorological model	1993	J94c, J96b	Yes	362
Temperature-dependence of quantum yields	1993	J94c, J96b	Yes	363
Solar-IR, thermal-IR gas absorption				
Spectral absorption coefficients from T89 in 3-D	1990	J94c, J96b	Yes	364
H ₂ O, CO ₂ , CH ₄ , O ₃ , O ₂	1990	J94c, J96b	Yes	365
Spectral absorption coefficients from M97 in 3-D	1996	J98b	Yes	366
H ₂ O, CO ₂ , CH ₄ , O ₃ , N ₂ O, CH ₃ Cl, CFC1 ₃ , CF ₂ Cl ₂ , CCl ₄	1996	J98b	Yes	367
Multiple absorber method	2001	J05b	Yes	368
Spectral absorption coefs. parameterized from HITRAN data	2001	J05b	Yes	369
Method accounts for multiple absorbing gases simultaneously	2001	J05b	Yes	370
H ₂ O, CO ₂ , CH ₄ , CO, O ₃ , O ₂ , N ₂ O, CH ₃ Cl, CFC1 ₃ , CF ₂ Cl ₂ , CCl ₄	2001	J05b	Yes	371
Function of temperature, pressure, mixing ratio	2001	J05b	Yes	372
Currently 592 solar-IR and thermal-IR wavelengths and probability intervals in each grid cell	2001	J04d, J05b	Yes	373
Spectral surface albedos / emissivities				
Snow / sea ice albedo / emissivity predicted	2002	J04d	Yes	374
Rad. transfer solved through many air layers, one snow or ice layer	2002	J04d	Yes	375
Albedo, emissivity = upward/downward irradiance above snow or ice	2002	J04d	Yes	376
Accounts for absorption by BC in snow/ice from dry deposition	2002	J04d	Yes	377
Accounts for absorption by BC in snow/ice from precipitation	2002	J04d	Yes	378
Accounts for absorption by soildust in snow/ice from dry deposition	2006	J07c	Yes	379
Accounts for absorption by soildust in snow/ice from precipitation	2006	J07c	Yes	380
Prognostic equation for concentration of chemicals in snow	2006	J07c	Yes	381
Accounts for precipitation and dry deposition source	2006	J07c	Yes	382
Accounts for burial and sinking of chemicals through snow	2002	J04d	Yes	383
Ocean water albedos/emissivities predicted	2003	J07a	Yes	384
Refractive index of ocean water a function of composition	2003	J07a	Yes	385

Other surfaces, albedos/emissivities from 1-km data	1999	J01d		
Daily variation of Earth-sun distance for spectral radiative transfer	1990	J99d, J05d	Yes	386
Zenith angle affected by space-atm. refraction for spectral rad, transfer	2002	J04d	Yes	387
Topographical shading for spectral radiative transfer	2000	J04d	Yes	388
Separate column spectral radiative transfer calc. for clear/cloudy sky	2000	J02b	Yes	389
Results weighed by cloud fraction to obtain grid-cell averaged spectral irradiances, actinic fluxes	2000	J02b	Yes	390
Surface processes				
Bare-soil, grid-scale subsurface (10-layer) soil moisture module	1993	L95	No	
Sixteen subgrid classes (13 soil, 1 water, 1 road, 1 rooftop) in each cell	1999	J01c	Yes	391
Fractions of each class determined from soil, landuse data	1999	J01c	Yes	392
Vegetation fraction over each subgrid soil class in each grid cell	1999	J01c	Yes	393
Determined from landuse, vegetation data	1999	J01c	Yes	394
Landuse data				
Provides canopy height over each subgrid soil class in each cell	1999	J01c	Yes	395
Provides road/rooftop fraction in each cell	1999	J01c	Yes	396
Provides water (lakes and oceans) fraction in each cell	1999	J01c	No	
Provides agricultural fraction of each subgrid soil class in each cell	2006	J07c	Yes	397
Determination of albedo of agricultural versus nonagricultural land from agricultural fraction and observed albedo of mixed pixel	2006	J08b	Yes	398
LAI in each subgrid soil class found by combining veg. fraction of each class with grid-cell-averaged LAI from 1-km data, ensuring soil-class LAI weighted by veg. fraction equals grid-cell LAI	2007		Yes	399
Treats daily irrigation in each grid cell for California	2006	J08b	Yes	400
Equations developed to solve subgrid snow depth	1999	J01c	Yes	401
Snow depth increases due to precipitation of size-resolved ice and graupel and due to vapor deposition at surface	1999	J01c, J03	Yes	
Snow depth decreases due to melting at top or bottom of snow layer and sublimation at top of snow layer	1999	J01c, J04d	Yes	402
Equations developed to solve subgrid sea ice depth	1999	J01c	Yes	403
Sea ice depth increases due to precip. of size-resolved ice, graupel, vapor deposition at surface	1999	J01c, J03	Yes	404
Sea ice depth decreases due to melting at top or bottom of ice layer and sublimation at top of ice layer	1999	J01c, J04d	Yes	405
Equations developed to solve surface/soil temperature/moisture over				
Subgrid soil covered with vegetation	1999	J01c	Yes	406
Calculates temp/moisture of foliage, air in foliage, ground iteratively	1999	J01c	Yes	407
Calculates soil temperature/moisture below subgrid surface over time	1999	J01c	Yes	408
Subgrid soil covered with snow over vegetation	1999	J01c	Yes	409
Subgrid bare soil covered with snow	1999	J01c	Yes	410
Subgrid roads	1999	J01c	Yes	411
Accounts for conduction between road surface and soil below	1999	J01c	Yes	412
Accounts for dew/rain accumulation/runoff on road surfaces	1999	J01c	Yes	413
Subgrid rooftops	1999	J01c	Yes	414
Accounts for multiple layers of different roofing material	1999	J01c	Yes	415
Accounts for conduction between rooftops and air below rooftops	1999	J01c	Yes	416
Accounts for dew/rain accumulation/runoff on rooftops	1999	J01c	Yes	417
Subgrid roads/rooftops covered with snow	1999	J01c	Yes	418
Subgrid water bodies	1999	J01c	Yes	419
Subgrid water bodies covered with sea ice	1999	J01c	Yes	420

Subgrid water bodies covered with snow over sea ice	1999	J01c	Yes	421
Grid-scale radiative, latent heat, sensible heat fluxes calculated from subgrid fluxes, weighted by subgrid surface class fraction	1999	J01c	Yes	422
Energy release during biomass burning added to the thermodynamic energy equation in each surface grid cell where burning occurs.	2006	J09a	Yes	423
Ocean dynamics / chemistry				
Equilibrium chemistry in coupled atmosphere-ocean model is solved in 10 layers below the surface of each ocean grid cell and below each subgrid surface water class (e.g., lakes)	2004	J05c	Yes	424
Ocean-atmosphere exchange solved for all atmospheric gases between each top water layer and the air	2004	J05c	Yes	425
Vertical diffusion of all chemicals solved in all subsurface water layers	2004	J05c	Yes	426
2-D ocean dynamics is solved globally in the surface mixed layer	2001	K07, J02b	No	
Vertical diffusion of energy solved in all subsurface water layers	2004	J07d	No	
CO ₂ chemical weathering loss at ocean bottom	2008	J09b	No	
3-D Ocean equilibrium chemistry				
EQUISOLV O solver	2004	J05c	Yes	427
Conserves moles, charge, unconditionally stable, positive-definite	2004	J05c	Yes	428
Solves any number of ion-liquid-solid equilibrium equations	2004	J05c	Yes	429
Now: Na-Cl-Mg-Ca-K-H-O-Li-Sr-C-S-N-Br-F-B-Si-P system	2004	J05c	Yes	430
Accounts for nonideality of ocean solutions	2004	J05c	Yes	431
Solves ocean ionic and molecular composition, including carbon	2004	J05c	Yes	432
Used to determine composition of sea spray emissions	2007	J09a	Yes	433
Solves ocean pH, salinity, alkalinity, density, ionic strength	2004	J05c	Yes	434
Ocean-atmosphere exchange				
OPD (Ocean Predictor of Dissolution) solver	2004	J05c	Yes	435
Transfers all model gases between atmosphere and ocean	2004	J05c	Yes	436
Accounts for current ocean composition from EQUISOLV O	2004	J05c	Yes	437
Noniterative, conserves moles, unconditionally stable, pos.-definite	2004	J05c	Yes	438
2-D ocean dynamics scheme of K07				
Predicts velocities, mixed-layer depths, temperatures in online coupled air quality-meteorological-ocean model	2001	K07, J02b	Yes	439
Conserves potential enstrophy in frictionless, barotropic flow limit	2001	K07, J02b	Yes	440
Conserves total energy for frictionless, adiabatic flow	2001	K07, J02b	Yes	441
Conserves potential enthalpy for adiabatic flow and mass	2001	K07, J02b	Yes	442
Ocean temperatures feed back to spectral radiative transfer	2001	J02b	Yes	443
Ocean temperatures feed back to sea ice depth	2001	J02b	No	
Ocean temperatures feed back to ocean composition in online coupled air quality-meteorological-ocean model	2004	J05c	Yes	444
Ocean temperatures feed back to ocean/atmosphere exchange	2004	J05c	Yes	445
Ocean temperatures feed back to ocean albedo, emissivities	2003	J07a	Yes	446
Vertical diffusion of energy / chemicals to deep ocean				
10 layers below the all ocean grid cell surfaces	2004	J05c	No	
Unconditionally stable 2 nd -order solution to diffusion	2004	J07d	No	
Scheme conserves moles/number and constant mixing ratio exactly	2004	J07d	?	
Diffuses all dissolved gas, ions, solids, and energy in ocean	2004	J07d	Yes	447

AEI	= Analytical equilibrium iteration
AGCM	= UCLA Atmospheric General Circulation Model
AP	= aerosol particles
APC	= Analytical Predictor of Condensation scheme
APD	= Analytical Predictor of Dissolution scheme
APNDC	= Analytical Predictor of Nucleation, Condensation, and Dissolution scheme
AS	= Arakawa-Schubert cumulus parameterization
CCN	= cloud condensation nuclei
COAGSOLV	= coagulation solver
DEMA	= Dynamic Effective Medium Approximation
DSCRAP	= discrete size- and composition-resolved aerosol particles
DSCRHP	= discrete size- and composition-resolved hydrometeor particles
EQUISOLV	= gas-aerosol chemical equilibrium solver
EQUISOLV II	= gas-aerosol chemical equilibrium solver, version II
EQUISOLV O	= ocean chemical equilibrium solver
GATOR	= Gas, Aerosol, Transport, and Radiation model
GATORG	= Gas, Aerosol, Transport, Radiation, and General circulation model
GATOR-GCMM	= Gas, Aerosol, Transport, Radiation, General Circulation, and Mesoscale Model
GATOR-GCMOM	= Gas, Aerosol, Transport, Radiation, General Circulation, Mesoscale, and Ocean Model
GATORM	= Gas, Aerosol, Transport, Radiation, and Mesoscale model
GCM	= General Circulation Model
HP	= hydrometeor particles
IDN	= ice deposition nuclei
LAI	= one-sided leaf-area index
MFI	= mass-flux iteration
MMTD	= Mesoscale Meteorological and Tracer Dispersion model
NIR	= near (solar) infrared
PAR	= photosynthetically-active radiation
PNG	= Predictor of nonequilibrium growth
RH	= relative humidity
SMVGEAR	= Sparse-matrix, vectorized Gear code
SMVGEAR II	= Sparse-matrix, vectorized Gear code, version II
TIR	= thermal (far) infrared
UV	= ultraviolet
ZSR	= Zdanovskii, Stokes, Robinson method

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