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

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Background

GATOR-GCMOM is a one-way nested (from the global to local scale) gas, aerosol, transport, radiation, general circulation, mesoscale, and ocean model.

In 1990, the model began as GATOR, a regional-scale gas, aerosol, radiation, and transport model. The model treated gas photochemistry, size- and composition-resolved aerosol microphysics and chemistry, wavelength-resolved solar and thermal-infrared radiative transfer, and horizontal and vertical transport of all gases and aerosol components. Time-dependent aerosol and gas optical properties fed into the radiative transfer calculation, thereby affecting photolysis and heating rates, thus photochemistry and temperature changes, respectively. However, temperature changes could not yet feed back to the weather.

In 1993, GATOR was coupled with a regional-scale dynamical meteorological module (MMTD). The coupled model now treated feedback of gases and size- and composition-resolved aerosol particles to meteorology through temperature changes calculated with the radiative transfer code. Changes in temperature affected pressure and pressure gradients, thereby affecting winds and turbulence. Temperature changes also affected evaporation rates, the relative humidity, and cloudiness. Changes in winds, turbulence, humidity, and cloudiness fed back to gas and aerosol concentration and composition. The result was the first online, coupled (with two-way feedback) regional air quality-meteorological model worldwide, GATORM (also called GATOR-MMTD).

In 1994, a global version of the model was developed that included gases, aerosols, radiation, transport, and dynamical meteorology. It accounted 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. This was the first online, two-way coupled global air quality-weather-climate model worldwide.

In 1998, GATORM and GATORG were linked together from the global to local scale, 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 (as opposed to grid-scale) surface parameterizations were added and aerosol numerics, including treatment of aerosols among multiple size distributions, were improved. All processes in all nested domains were exactly the same, except for the different horizontal boundary conditions and solutions to the momentum equation on the global versus regional scale. The model has since been applied from the global scale down to a horizontal resolutions of 10 m.

In 2000, treatment of discrete size-resolved cloud hydrometeor particles containing multicomponent aerosol inclusions was added. The hydrometeor particles existed in multiple size distributions (liquid, ice, and graupel) and interacted among each other and between multiple size distributions of discrete size- and composition-resolved aerosol particles. 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 subgrid aircraft exhaust microphysics and plume expansion from each individual commercial aircraft flight worldwide at the subgrid scale was added.

In 2009, near-explicit gas photochemistry (over 4600 species and 13,500 reactions) was added along with the transport, radiative heating, and photolysis of all explicit gases. GATOR-GCMOM thus became the first atmospheric model to simulate 3-D near-explicit photochemistry on the regional and global scales. In 2012, highly-explicit aqueous chemistry (390 species and 829 reactions) was coupled with the near-explicit gas photochemistry in 3-D.

In 2011, treatment of the extraction of energy from the atmospheres by wind turbines on the regional and global scales was added, allowing for the first calculation of the saturation wind energy potential of the world.

Table 1 compares treatment of online coupling of several major processes in GATOR-GCMOM with that in prior or concurrent models that treated some coupling. Whereas, several 3-D models had some form of coupling, none on the global or regional scale prior to GATOR-GCMOM in 1995 (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	J10b
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-resolved aerosol particles							Y	Y	Y	Y
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							Y	Y	Y	Y

from spectral solar and thermal-IR radiative transfer										
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 calculated from spectral radiative transfer							Y	Y	Y	Y
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 ~500 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 treat-ment 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, meteorological parameters at horiz. 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	K09, 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	J11b	Yes	28
First 3-D Model to Treat Near-Explicit Photochemistry				
Near-explicit 3-D photochemistry (>13,500 reactions) in GATOR-GCMOM	2009	J10b	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_2O, H_2, CH_4, NO, NO_2, N_2O, NH_3, SO_2, COS, CH_3Cl, CH_3Br, CH_3SCH_3, CH_3SSCH_3, C_2H_6, C_2H_4, C_3H_8, C_3H_6, C_4H_{10}, C_4H_8, C_4H_6, C_5H_{12}, C_5H_{10}, C_5H_8, C_6H_6, toluene, monoterpenes, xylene, ethylbenzene, CH_3OH, C_2H_5OH, HCHO, CH_3CHO, CH_3COCH_3, benzaldehyde, HCOOH, CH_3COOH	2000	J02b	Yes	31
Biofuel burning separated from other emissions	2003	J04d	Yes	32
Same chemicals as open biomass burning	2003	J04d	Yes	33
Includes H_2O from combustion	2004	J04d	Yes	34
Vehicles, power plants, industry, homes, etc.	1993	J96b	No	
Same chemicals as open biomass burning	1993	J96b	Yes	35
Includes H_2O from combustion	2000	J02b	Yes	36
Includes H_2O from power-/manuf.-plant cooling-water evaporation	2010	J12d	Yes	37
Plume rise equation for stack emissions	1993	J96b	No	
Shipping	2000	J02b, J06a	No	
CO_2, CO, H_2O, H_2, CH_4, NO, NO_2, HONO, N_2O, SO_2, HSO_3,H_2SO_4	2000	J02b, J06a	Yes	38
Aircraft	2005	J07a	No	
CO_2, CO, H_2O, H_2, CH_4, NO, NO_2, HONO, N_2O, SO_2, HSO_3, H_2SO_4, speciated NMVOC	2005	J07a	Yes	39
Gas emissions from all individual flights worldwide at subgrid scale	2007	J11b	Yes	40
All gases emitted into individual subgrid contrail plumes in each cell	2012	J12e	Yes	41
Gas chemistry solved separately within each subgrid plume	2012	J12e	Yes	42
Subgrid gases released to grid scale when contrail dissipates	2012	J12e	Yes	43

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	44
Monoterpenes	2003	J05f	No	
Other volatile organic carbon	2003	J05f	No	
Carbon dioxide from plant respiration	2006	J09	No	
Soil bacteria respiration				
NO	1996	J05f	No	
H_2, N_2O, CO_2	2006	J09	No	
Carbon dioxide				
Plant cellular respiration / photosynthesis	2006	J09	No	
Phytoplankton respiration / photosynthesis	2008	J11b	No	
Soil bacteria respiration	2006	J09	No	
Ocean evaporation (see ocean-atmosphere exchange)	2004	J05c	No	
Lightning, hot channel and corona discharge	2000	J02b, J09	No	
NO, NO_2, HONO, N_2O, HNO_3, CO, H_2O_2, HO_2	2000	J02b, J09	Yes	45
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, J09	Yes	46
Volcanos, sporadic and continuous	2000	J02b	No	
H_2O, CO_2, CO, H_2, SO_2, H_2S, CS_2, OCS, HCl, HBr, HF	2000	J02b	Yes	47
Ocean biological production of CH_4, H_2, N_2O	2006	J09	No	
Anthropogenic DSCRAP emissions				
Open biomass burning	2000	J01b, J02b	No	
BC, POM, $H_2O(l)$, NH_4^+, Na^+, K^+, Mg^{2+}, Ca^{2+}, H^+, $H_2SO_4(aq)$, HSO_4^-, SO_4^{2-}, Cl^-, Br^-, NO_3^-, HCO_3^-	2000	J01b, J02b	Yes	48
Biofuel burning separated from other emissions	2003	J04d	Yes	49
Same chemicals as open biomass burning	2003	J04d	Yes	50
Vehicles, power plants, industry, homes, etc.	1993	J97b	No	
Same chemicals as open biomass burning	1993	J97b	Yes	51
Plume rise equation for stack emissions	1993	J96b	No	
Spatial emissions of explicit gases for near-explicit photochemistry	2009	J10b	Yes	52
Shipping	2000	J02b, J06a	No	
BC, POM	2000	J02b, J06a	No	
Aircraft	2005	J07a	No	
BC, POM, H^+, $H_2SO_4(aq)$, HSO_4^-, SO_4^{2-}	2005	J07a	Yes	53
Emissions from all individual commercial aircraft worldwide	2007	J11b	Yes	54
Each individual contrail tracked as a subgrid tube in each grid cell	2007	J11b	Yes	55
Contrails form by deposition of aircraft H_2O on DSCRAP emission	2007	J11b	Yes	56
Contrail ice crystals grow by collision-coalescence/H_2O deposition	2007	J11b	Yes	57
Contrail plumes spread by subgrid shearing and dilution	2007	J11b	Yes	58
Contrail ice sublimated upon sufficient dilution in each plume	2007	J11b	Yes	59
Contrail merges with grid-scale material upon dilution to grid scale$_2$	2007	J11b	Yes	60
Road dust	1993	J97b	No	
BC, POM, NH_4^+, Na^+, K^+, Mg^{2+}, Ca^{2+}, H^+, $H_2SO_4(aq)$, HSO_4^-, SO_4^{2-}, Cl^-, NO_3^-, Fe, Al, Si	2004		Yes	61

Natural DSCRAP emissions				
Sea spray and spume drops	1994	J97b	No	
$H_2O(aq)$, Na^+, K^+, Mg^{2+}, Ca^{2+}, H^+, $H_2SO_4(aq)$, HSO_4^-, SO_4^{2-}, Cl^-, Br^-, NO_3^-, HCO_3^-, POM	1994	J97b	Yes	62
Function of wind speed	1994	J97b	No	
Use modeled seawater composition (see ocean equilibrium chem..)	2007	J09	Yes	63
Soil dust	2000	J01b	No	
Na^+, K^+, Mg^{2+}, Ca^{2+}, $SiO_2(s)$, $Fe_2O_3(s)$, $Al_2O_3(s)$	2000	J01b	Yes	64
Function of wind speed	2000	J01b	No	
Function of subgrid soil class, each with diff. composition	2000	J01b	Yes	65
Pollen	2005	J09	Yes	66
Fungal spores	2005	J09	Yes	67
Bacteria from soils	2005	J09	Yes	68
Bacteria from the ocean	2005	J09	Yes	69
Volcanos, sporadic and continuous	2000	J02b	No	
SO_4^{2-}, Na^+, K^+, Ca^{2+}, Fe, Al, Zn	2000	J02b	Yes	70
Gas photochemistry and transport				
Fully-coupled online tropospheric chemistry-radiation-meteorology	1993	J94c, J96b	Yes	71
Near-explicit gas photochemistry solved in 3-D coupled model	2009	J10b	Yes	72
All absorbing gases from online spectral photochemistry feed back to dynamics through spectral heating rates	1993	J94c, J96b	Yes	73
All chemically-active gases transported in 3-D (none in steady state)	1993	J94c, J96b	Yes	74
Horizontal advection and vertical convection of all gases	1993	J94c, J96b	Yes	75
Horizontal and vertical molecular diffusion of all gases	1993	J94c, J96b	Yes	76
Vertical turbulent diffusion of all gases	1993	J94c, J96b	Yes	77
All gases involved in photochemistry are solved with time-dependent exact solution (no steady state or approximations)	1993	J94c, J96b	Yes	78
Fully-coupled online global trop/strat. chemistry-radiation-meteorology	1994	J95c, J01c	Yes	79
All absorbing gases, including ozone, from online spectral photochemistry feed back to dynamics through spectral heating rates	1994	J95c, J01c	Yes	80
All absorbing gases from near-explicit mechanism feed back to dynamics through spectral heating rates	2009	J10b	Yes	81
All gases solved during photochemistry are transported in 3-D	1994	J95c, J01c	Yes	82
All gases in near-explicit mechanism are transported in 3-D	2009	J10b	Yes	83
All gases involved in photochemistry are solved with time-dependent exact solution (no steady state or approximations).	1994	J95c, J01c	Yes	84
All gases in near-explicit mechanism solved with exact solution	2009	J10b	Yes	85
Photochemistry produces inorganic and organic gases used for size-resolved aerosol growth in coupled gas-aerosol-meteorological model	1994	J97a	Yes	86
Development of method of converting pseudo-first-order to second-order rate coefficients to ensure mass conservation of heterogeneous reactions	2006	J08c	Yes	87
Family chemistry solution scheme	1990	J94c, J99d	No	
Matrix inversion to solve for species concentrations in family	1990	J94c, J99d	Yes	88
Multistep implicit-explicit (MIE) solution scheme	1992	J94a	Yes	89
Iterated forward and backward Euler converge to each other	1992	J94a	Yes	90
SMVGEAR / SMVGEAR II	1993	J94a, J98a	Yes	91
Near-exact solution to first-order ODEs, based on Gear's method	1993	J94a	Yes	92
Predicts the time step (10^{-10} to 900 s)	1993	J94a	Yes	93

Predicts the order of convergence (1st to 5th)	1993	J94a	Yes	94
Uses a variable relative error tolerance (default is 10^{-3})	1993	J94a	Yes	95
Uses a variable absolute error tolerance	1993	J94a	Yes	96
Predicted absolute error tolerance (SMVGEAR II)	1997	J98a	Yes	97
Sparse matrix techniques				
Species with fewest partial derivative terms at top of matrix	1993	J94a	Yes	98
Eliminate matrix decomposition/backsubstitution multiplies by zero	1993	J94a	Yes	99
Compress matrix arrays to minimize memory	1993	J94a	Yes	100
Separate matrices for day/night chemistry	1993	J94a	Yes	101
Division of grid domain into blocks of grid cells	1993	J94a	Yes	102
Vectorization around the grid cell dimension in each block	1993	J94a	Yes	103
Minimizes array references on vector and scalar machines	1993	J94a	Yes	104
Speeds array operations on vector machines	1993	J94a	Yes	105
Less memory than vectorization around full domain.	1993	J94a	Yes	106
Reordering of grid cells among all blocks by stiffness	1994	J95b	Yes	107
Allows stiff cells and non-stiff cells to be solved together	1994	J95b	Yes	108
Division of domain into grid blocks used parallelization	2001	J94a	Yes	109
Different sets of chemistry for different regions of atmosphere	1994	J95b	Yes	110
First derivatives, partial derivatives, matrices automatically generated from a changeable input species and reaction date set.	1993	J94a	Yes	111
Photolysis coefficients updated each SMVGEAR time step	1993	J94a	Yes	112
Interpolated between coefficients calculated from spectral radiative transfer at the begin and end of each chemistry time interval	1993	J94a	Yes	113
Discrete size- and composition-resolved aerosol processes				
Characteristics of aerosol size distributions				
Any number of aerosol size distributions	1991	J94b	Yes	114
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	115
Predicts mole conc. of each chem. in each bin of each distribution	1991	J94b	Yes	116
Single-particle volume consists of solution + nonsolution component	1998	J02a	Yes	117
Solution density determined from densities of electrolytes	1998	J02a	Yes	118
Aerosol size structures (how size distributions vary in time)				
Hybrid	1993	J95a	Yes	119
Constant core volume but variable shell volume	1993	J95a	Yes	120
Moving center	1994	J97a	Yes	121
Particles moved when larger/smaller than bin boundaries	1994	J97a	Yes	122
Full moving	1993	J95a	N/A	
Particles moved to their exact volumes. (0-D only)	1993	J95a	N/A	
Quasistationary	1994	J97a	Yes	123
Number/volume partitioned between adjacent bins	1994	J97a	Yes	124
Nucleation				
Homogeneous homomolecular and binary nucleation	1991	J94c, J97a	No	
Homogeneous ternary nucleation	2003	J06a	Yes	125
Heterogeneous homomolecular and binary nucleation	1991	J99d, J05d	No	
Nucleation solved simultaneously with condensation	1993	J02a	Yes	126
Aerosol-aerosol coagulation				
COAGSOLV noniterative solver for discrete size distributions	1993	J94b	Yes	127

Positive-definite, unconditionally stable for any time step	1993	J94b	Yes	128
Conserves single-particle volume of total particle, all components	1993	J94b	Yes	129
Conserves volume concentration of total particle, all components	1993	J94b	Yes	130
Solves equations for any volume ratio of adjacent size bins > 1	1993	J94b	Yes	131
Solves any number externally-, one internally-mixed distribution	1993	J94b	Yes	132
Solves any number externally- and internally-mixed distributions	2000	J01b, J02a	Yes	133
Solves for particle number of all sizes of all distributions	1993	J94b	Yes	134
Solves for all individual components of all sizes of all distributions	1993	J94b	Yes	135
Discrete size-resolved aerosol-aerosol coagulation kernels over time	1993	J94b	Yes	136
Brownian diffusion	1993	J94b	Yes	137
Brownian diffusion enhancement	1993	J94b	Yes	138
Turbulent shear	1993	J94b	Yes	139
Turbulent inertial motion	1993	J94b	Yes	140
Gravitational settling	1993	J94b	Yes	141
Van der Waals forces	2003	J04a	Yes	142
Viscous forces	2003	J04a	Yes	143
Fractal geometry	2003	J04a	Yes	144
Equilibrium chemistry within aerosols and between gases/aerosols				
Coupling size-resolved equilibrium with dissolutional growth in 3-D	1991	J96a	Yes	145
Aerosol equilibrium for vapor pressures within all DSCRAP in all size distributions	1991	J96a	Yes	146
Vapor pressures for nonequilibrium dissolutional growth	1991	J96a	Yes	147
Internal aerosol equilibrium for composition after growth	1991	J96a	Yes	148
Equilibrium between gases and all DSCRAP in 3-D model	1991	J96a	No	
EQUISOLV chemical equilibrium solver	1991	J96a	Yes	149
Solves any number equations among gases, ions, liquids, solids	1991	J96a	Yes	150
e.g., H_2O(l), H_2SO_4(aq), HSO_4^-, SO_4^{2-} , NO_3^-, Cl^-, H^+, NH_4^+, Na^+	1991	J96a	Yes	151
Solid formation depends on deliquescence and crystallization RHs, and whether RH is increasing or decreasing	1991	J96a	Yes	152
Determines aerosol pH, liquid water content and composition	1991	J96a	Yes	153
Uptake of water reduces the relative humidity iteratively, feeding back to water uptake and aerosol composition	2002	J08a	Yes	154
Uptake of water warms air temperature iteratively	2002	J08a	Yes	155
Numerical solution iterative around all equations	1991	J96a	Yes	156
Unconditionally stable, positive definite, conserves moles, charge	1991	J96a	Yes	157
Individual equations solved with MFI method	1991	J96a	Yes	158
Iterative, exact solution to individual equations	1991	J96a	Yes	159
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	160
EQUISOLV II chemical equilibrium solver	1997	J99c	Yes	161
Solves any number equations among gases, ions, liquids, solids	1997	J99c	Yes	162
e.g., H_2O(l), H_2SO_4(aq), HSO_4^-, SO_4^{2-}, HNO_3(aq), NO_3^-, Cl^-, H_2CO_3(aq), HCO_3^-, CO_3^{2-}, H^+, NH_4^+, Na^+, Mg^{2+}, Ca^{2+}, K^+	1997	J99c	Yes	163
e.g., 25 or more solid electrolytes can form	1997	J99c	Yes	164
Solution iterative around all equations,	1997	J99c	Yes	165
Unconditionally stable, positive definite, conserves moles, charge	1997	J99c	Yes	166
Individual equations solved with AEI method	1997	J99c	Yes	167
Exact analytical solution to individual equations	1997	J99c	Yes	168

Dissolutional growth/evaporation between gases/DSCRAP				
Dissolution of inorganic gases into DSCRAP	1993	J95a	Yes	169
Dissolution of organic gases into DSCRAP	1994	J97a, J04d	Yes	170
Dissolution into multiple aerosol distributions simultaneously	1998	J02a	Yes	171
SMVGEAR solution to dissolution	1993	J96a	Yes	172
Exact solution	1993	J96a	Yes	173
Conserves moles between gas and all particle size bins	1993	J96a	Yes	174
Effective Henry's constants/vapor pressures from EQUISOLV	1993	J96a	Yes	175
APD solution to dissolution	1993	J97c	Yes	176
Noniterative, analytical solution to discretized equation	1993	J97c	Yes	177
Unconditionally-stable, positive definite	1993	J97c	Yes	178
Conserves moles between gas and all particle size bins	1993	J97c	Yes	179
Effective Henry's constants/vapor pressures from EQUISOLV	1993	J97c	Yes	180
APNCD solution	1998	J02a	Yes	181
Solves nucleation, condensation, dissolution together	1998	J02a	Yes	182
Solves equations between gas and multiple size distributions	1998	J02a	Yes	183
Allows condensation in some bins, dissolution in others	1998	J02a	Yes	184
Noniterative, unconditionally stable, positive definite	1998	J02a	Yes	185
Conserves moles between gas and all bins in all distributions	1998	J02a	Yes	186
Effective Henry's constants/vapor pressures from EQUISOLV II	1998	J02a	Yes	187
PNG-EQUISOLV II solution	2003	J05a	Yes	188
Couples dissolution growth/equilibrium at long time step	2003	J05a	Yes	189
Dissolution of semivolatile acid gases at high/moderate LWC	2003	J05a	Yes	190
pH, aerosol comp. for effective Henry's const. from EQUISOLV II	2003	J05a	Yes	191
Condensation of semivolatile acid gases at low LWC	2003	J05a	Yes	192
Vapor pressure determined over solids from analytical solution	2003	J05a	Yes	193
Vapor pressure determined over liquids from EQUISOLV II	2003	J05a	Yes	194
Condensation involatile gases at all LWC	2003	J05a	Yes	195
Equilibration $NH_3/NH_4^+$and pH between gas/all distributions	2003	J05a	Yes	196
Equilibration of internal-aerosol liquid, ion, solids, pH, LWC	2003	J05a	Yes	197
Conserves moles/charge between gas and all size distributions	2003	J05a	Yes	198
Solution method stable, nonoscillatory at long time step	2003	J05a	Yes	199
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	200
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	201
Radiative cooling effect term	1991	J95a	Yes	202
SMVGEAR solution	1993	J95a	Yes	203
Exact solution to condensation/evaporation	1993	J95a	Yes	204
Conserves moles between gas and all aerosol size bins	1993	J95a	Yes	205
APC solution	1993	J97c	Yes	206
Noniterative, analytical solution to discretized equation	1993	J97c	Yes	207
Unconditionally-stable, positive definite	1993	J97c	Yes	208
Conserves moles between gas and all aerosol size bins	1993	J97c	Yes	209
APNCD solution	1998	J02a	Yes	210
Solves nucleation, condensation, dissolution together	1998	J02a	Yes	211

Solves equations between gas and multiple size distributions	1998	J02a	Yes	212
Noniterative, unconditionally stable, positive definite	1998	J02a	Yes	213
Conserves moles between gas and all bins in all distributions	1998	J02a	Yes	214
Aqueous chemistry (irreversible)				
Solved within DSCRAP, operator split from gas-aerosol transfer	1992	J97a	Yes	215
Solved together with gas-aerosol transfer to all discrete size bins	1997	J99d, J05d	Yes	216
Gas transfer/chemistry of families solved with SMVGEAR	1997	J99d, J05d	Yes	217
Families partitioned to ions with EQUISOLV	1997	J99d, J05d	Yes	218
Gas transfer/chemistry to liquid aerosol/hydrometeor particles together	2000	J02b, J03	Yes	219
Highly-explicit aqueous photochemistry coupled with near-explicit gas photochemistry solved in 3-D coupled model	2012	G12	Yes	220
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	221
All chemicals in all sizes in all HP size distributions transported	2000	J02b, J03	Yes	222
HP number concentration in each bin transported as well	2000	J02b, J03	Yes	223
Gas, interstitial DSCRAP are transported consistently	2000	J02b, J03	Yes	224
Convective plume module transported gases, DSCRAP, DSCRHP	2000	J02b, J03	Yes	225
Conserves moles / number exactly	2000	J02b, J03	Yes	226
Turbulent diffusion scheme transports gases, DSCRAP, DSCRHP	2004	J07d	Yes	227
Conserves moles and constant mixing ratio exactly	2004	J07d	Yes	228
Resolved scales (grid-scale clouds)				
DSCRHP and inclusions are transported in 3-D over time	2005	J07b	Yes	229
All chemicals in all DSCRHP size distributions are transported	2005	J07b	Yes	230
DSCRHP number concentration in each bin transported as well	2005	J07b	Yes	231
Modeled grid-scale velocities used to transport material	2005	J07b	No	
Same advection/diffusion solvers as to transport gases, DSCRAP	2005	J07b	Yes	232
Discrete size/composition-resolved cloud microphysics (all scales)				
Microphysical processes are time-dependent and explicit	2000	J02b, J03	No	
Hydrometeor particles are discretely size and composition resolved	2000	J02b, J03	Yes	233

Three hydrometeor distributions can form: liquid, ice, graupel	2000	J02b, J03	No	
DSCRHP can form on any number of discrete aerosol distributions	2000	J02b, J03	Yes	234
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	235
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	236
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	237
All microphysical processes conserve water vapor, size-resolved aerosol and hydrometeor, precipitation, ground, and ocean water	2000	J02b, J03	Yes	238
All microphysical processes conserve energy	2000	J02b, J03	No	
In-cloud condensation/deposition/evap./subl. (nucleation scavenging)				
DSCRHP grow on a single DSCRAP distribution in a global model	2000	J02a, J03	Yes	239
DSCRHP grow on multiple aerosol size distributions	2000	J03, J06a	Yes	240
Aerosol surface tension, composition vary with size/distribution	2000	J02b, J03	Yes	241
Surface tension is function of organic, inorganic composition	2000	J02b, J03	Yes	242
Activated CCN/IDN size bins are determined from the Köhler equation applied to each aerosol size distribution in 3-D	2000	J02b, J03	Yes	243
Growth solution allows for dual peaks in cloud size distributions	2000	J03, J06a	Yes	244
Growth results in discrete liquid, ice, or both in all size distributions	2000	J02b, J03	Yes	245
DSCRHP contain inclusions of all aerosol components they form on	2000	J02b, J03	Yes	246
Heterogeneous nucleation (HN) of ice determined by considering size and composition of size-resolved aerosol particles	2000	J02b, J03	Yes	247
HN accounts for minimum embryo radius on each aerosol size.	2008	J10c, J11b	Yes	248
HN accounts for temperature- and size-dependence of freezing probability	2008	J10c, J11b	Yes	249
Ice crystal shape is a function of temperature and size. Shape affects capacitance, fall speed, coagulation kernel, diffusion coefficient	2010	J11b	No	
Solution to hydrometeor growth is extension of APC scheme	2000	J03, J07b	Yes	250
Water vapor competes between liquid and ice during growth onto CCN and IDN aerosol distributions	2000	J03	Yes	251
Water vapor competes among liquid CCN aerosol, ice IDN aerosol, and pre-existing liquid, ice, graupel hyd. distribs. during growth	2000	J07b	Yes	252
Noniterative, unconditionally-stable, positive definite	2000	J03	Yes	253
Conserves moles between gas and all bins of all distributions	2000	J03	Yes	254
Hydrometeor growth solved over quasistationary size structure	2000	J02b, J03	Yes	255
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	256
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	257
COAGSOLV used to solve hyd.-hyd. coagulation	2000	J02b, J03	Yes	258
Noniterative, pos.-definite, unconditionally stable for any time step	2000	J02b, J03	Yes	259
Conserves single-part. volume of total particle & all components	2000	J02b, J03	Yes	260
Conserves volume concentration of total particle & all components	2000	J02b, J03	Yes	261
Solves equations for any volume ratio of adjacent size bins > 1	2000	J02b, J03	Yes	262

Solves for particle number and component concentration	2000	J02b, J03	Yes	263
Components in each distribution coagulate with all distributions	2000	J02b, J03	Yes	264
Lightning formation (see natural emissions of gases)	2000	J05d, J09	Yes	265
Discrete size-resolved hydromet.-hydromet. coag. kernels over time	1993	J94b	Yes	266
Brownian diffusion	1993	J94b	Yes	267
Brownian diffusion enhancement	1993	J94b	Yes	268
Turbulent shear	1993	J94b	Yes	269
Turbulent inertial motion	1993	J94b	Yes	270
Gravitational settling	1993	J94b	No	
Diffusiophoresis	2000	J02b, J03	Yes	271
Thermophoresis	2000	J02b, J03	Yes	272
Electric charge	2000	J02b, J03	Yes	273
Aerosol-hydrometeor coagulation (aerosol washout)				
Coag. between interstitial aerosol distribs. and hydrometeor distribs.	2000	J03	Yes	274
Size- and distrib.-resolved aer.-liquid, aer.-ice, aer.-graupel coag.	2000	J03	Yes	275
DSCRAP and components coag. to DSCRHP distributions	2000	J03	Yes	276
COAGSOLV used (same as for hydrometeor-hydrometeor coag.)	2000	J02a	Yes	277
Components in each distribution coagulate with all distributions	2000	J03	Yes	278
Coagulated aerosol components incorporated into DSCRHP	2000	J03	Yes	279
Coagulation kernels (same as for hydrometeor-hydrometeor coag.)	1993	J94b, J03	Yes	280
Large liquid drop breakup				
Drops & inclusions fragmented to smaller sizes in global model	2000	J03	Yes	281
Discrete size-resolved drop breakup in global model	2010	J11a	Yes	282
Positive-definite, unconditionally stable for any time step	2010	J11a	Yes	283
Solves for particle number and component concentration	2010	J11a	Yes	284
Conserves single-particle volume of total particle & all components	2010	J11a	Yes	285
Conserves volume concentration of total particle & all components	2010	J11a	Yes	286
Size-resolved breakup and bounceoff enhance lightning	2010	J11a	Yes	287
Below-cloud evaporation/sublimation				
Iterative equation for drop surface temperature	2000	J03	Yes	288
Evaporation rate a function of drop surface temperature, size	2000	J03	Yes	289
Complete evaporation/sublimation, release of aerosol cores to air				
Evaporation/sublimation of all water releases DSCRAP to air	2000	J03	Yes	290
DSCRAP released back to mixed aerosol distrib.	2000	J03	Yes	292
Gas washout (dissolution of gases in precipitation)				
Gas dissolution/evap. in liquid precip. solved in vertical column	2000	J03	Yes	292
Supersaturation of gas in drops results in release to gas phase	2000	J03	Yes	293
Undersaturation of gas results in uptake of gas by precip.	2000	J03	Yes	294
Solution conserves moles between gas/precipitation	2000	J03	Yes	295
Irreversible aqueous chemistry in clouds				
Gas transfer / bulk aqueous chemistry solved with SMVGEAR	2000	J02b, J03	Yes	296
Gas transfer/chemistry to liquid aerosol/hydromet. particles together	2000	J02b, J03	Yes	297
Aqueous chemical products redistributed to discrete aerosol and hydrometeor sizes based on initial aer/hyd composition	2000	J02b, J03	Yes	298
Size-resolved aqueous chemistry in clouds with SMVGEAR	2000	J97a	Yes	299

Hydrometeor settling				
Hydrometeor fall speed function of size, density, air viscosity	2000	J03	Yes	300
Precipitation to ground				
Precipitation of size-resolved liquid increases soil water, runoff	1999	J01c	Yes	301
Precipitation of size-resolved ice, graupel increases snow depth	1999	J01c	Yes	302
Precipitation releases size-resolved aerosol inclusions to sea ice, snow	2000	J04d	Yes	303
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	304
Contact freezing				
Size-resolved coagulation of DSCRAP with liquid HP initiates freezing at subfreezing temperatures.	2000	J03	Yes	305
Solved with COAGSOLV	2000	J03	Yes	306
Freezing moves liquid HP and inclusions to graupel distribution	2000	J03	Yes	307
Evaporative freezing				
Below-cloud evaporation cools drop surface	2000	J03	Yes	308
Evaporation a function of drop surface temperature, size	2000	J03	Yes	309
Lower temperature enhances het./homogeneous freezing rate	2000	J03	Yes	310
Freezing moves liquid HP and inclusions to graupel distribution	2000	J03	Yes	311
Melting of ice crystals 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	312
Horizontal/vertical advection/diffusion				
All photochemically-active gases are transported in 3-D	1993	J94c, J96b	Yes	313
Winds/diffusion coefficients for advection/diffusion of gases, particles predicted by online dynamics module	1993	J94c, J96b	Yes	314
Region/global advec./diffusion w/ 4th-order finite element scheme of T89	1990	J94c, J96b	Yes	315
Used for all gases, AP, AP components of all sizes of all distributions	1990	J94c, J96b	Yes	316
Regional advection/diffusion w/ 2nd-order finite difference scheme used to transport water vapor, energy in MMTD	1996	J97d	Yes	317
Used for all gases, AP, AP components of all sizes of all distributions	1990	J96b	Yes	318
Change in air density during advection exactly consistent with change in air density from regional dynamics module	1990	J96b	Yes	319
Global advection w/ 13-point, 4th-order scheme of A95 used to transport water vapor energy in global dynamics module.	1995	J01c	Yes	320
Used for all gases, AP, AP components of all sizes of all distributions	1995	J01c	Yes	321
Change in air density during advection exactly consistent with change in air density from global dynamics module	1995	J01c	Yes	322
Global/regional advection/diffusion w/ positive-definite, monotonic, nonoscillatory scheme of W98/W00	1998	J01c	Yes	323
Used for all gases, AP, AP components of all sizes of all distributions	1998	J01c	Yes	324
Used for all HP and inclusions when clouds resolved	2005	J07b	Yes	325

Vertical diffusion operator split from advection				
Unconditionally stable 2nd-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	326
Used for all DSCRHP and inclusions in air when clouds are not resolved	2005	J07d	Yes	327
Used for all DSCRHP and inclusions in clouds when clouds are resolved	2005	J07d	Yes	328
Used for vertical diffusion all ocean chemicals	2004	J05c	Yes	329
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	330
Hybrid scheme of L95				
Regional scales	1993	J96b	No	
Global scale	1994	J01c	Yes	331
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	
Wind turbine momentum extraction to produce electricity and reduce winds				
Momentum extracted from winds by wind turbines in global model as a function of instantaneous wind speed, using turbine power curve	2012	J12c	Yes	332
Turbines resolved vertically in global and regional model when extracting momentum	2012	J12c	Yes	333
Momentum extraction from turbines directly to determine saturation wind power potential (SWPP) in jet streams and near surface in global model	2012	J12c	Yes	334
Conversion of electric power generation from wind turbines back to heat returned to the atmosphere.	2012	J12c	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	335
Wet deposition of gases				
All gases dissolve in/evaporate from liquid precip. (see gas washout)	2000	J03	Yes	336
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	2000	J03	Yes	337

washout. Precipitation particles that fall to the ground contain DSCRAP (see nucleation scavenging and aerosol washout)				
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	338
Use of spectral two-stream code of T89	1991	J94c, J96b	Yes	339
Feedback of time-varying gases to spectral radiative transfer for photolysis in online coupled air quality-meteorological model	1993	J94c, J96b	Yes	340
Feedback of time-varying DSCRAP to spectral radiative transfer for photolysis in an online coupled air quality-meteorological model	1993	J94c, J97b	Yes	341
Feedback of DSCRAP to ozone through photolysis in an online coupled 3-D air quality-meteorological model.	1993	J97b, J98b	Yes	342
Currently 84 UV and visible wavelengths for photolysis	2001	J04d, J05b	Yes	343
Online spectral radiative transfer for visibility in 3-D	1992	J94c	Yes	344
Online spectral radiative transfer for PAR in 3-D	2003	J05f	Yes	345
Online spectral (rather than broadband) UV/Vis/NIR/TIR radiative transfer for heating rates	1993	J94c, J96b	Yes	346
Use of spectral two-stream code of T89	1991	J94c, J96b	Yes	347
Feedback of time-varying gases to spectral radiative transfer for heating rates in online coupled air quality-meteorological model	1993	J94c, J96b	Yes	348
Feedback of time-varying DSCRAP to spectral radiative transfer for heating rates in online coupled air quality-meteorological model	1993	J94c, J97b	Yes	349
Feedback of time-varying DSCRAP to temperatures in an online coupled 3-D air quality-meteorological model	1993	J97b, J98b	Yes	350
Feedback of time-varying DSCRAP to winds through heating rates in an online coupled 3-D air quality-meteorological model	1993	J97b, J06b	Yes	351
Currently 676 wavelengths/probability intervals for heating rates	2001	J04d, J05b	Yes	352
84 UV and visible wavelengths	2001	J04d, J05b	Yes	353
224 NIR (28 wavelengths, each with 8 probability intervals)	2001	J04d, J05b	Yes	354
368 TIR (46 wavelengths, each with 8 probability intervals)	2001	J04d, J05b	Yes	355
Spectral optical properties of DSCRAP				
Spectral optical properties of all aerosol particles of all sizes in multiple size distributions.	1991	J94c, J97a, J02a	Yes	356
Spectral forward, total scattering/absorption efficiencies vs. size	1991	J94c,J97a,b	Yes	357
Mie solver for stratified spheres of T81 used	1991	J97a,b	Yes	358
Single particles in each size bin divided into core and shell in 3-D	1994	J97a	Yes	359
BC core / mixed shell	1994	J97a, J99b	Yes	360
Mixed core / ammonium nitrate shell	1997	J99b	Yes	361
Shells divided into solution/nonsolution components	2000	J02	Yes	362
Solution refractive indices from partial molar refraction theory	2000	J02	Yes	363
Size-resolved shells or cores include spectral UV/Visible absorption by				
Black carbon (BC)	1994	J97a, J99b	Yes	364
Ammonium nitrate	1997	J99b	Yes	365
Nitrated aromatic aerosols	1997	J99b	Yes	366
Benzaldehydes	1997	J99b	Yes	367
Benzoic acids	1997	J99b	Yes	368
Aromatic polycarboxylic acids	1997	J99b	Yes	369
Phenols,	1997	J99b	Yes	370
Polycyclic aromatic hydrocarbons (PAHs)	1997	J99b	Yes	371

Organic bases	1997	J99b	Yes	372
Iron oxide	1998	J01a	Yes	373
Aluminum oxide	1998	J01a	Yes	374
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	375
Spectral optics of discrete size- & composition-resolved HP (DSCRHP)				
Accounts for liquid, ice, and graupel discrete size distributions	2000	J02b, J03	Yes	376
Hydrometeor optical calculation historically assumed				
Pure liquid, ice, or graupel in each hydrometeor size bin	2000	J02b, J03	Yes	377
Liquid, ice, or graupel shell containing a single concentric BC core in each size bin (CSA approximation)	2004	J06a	Yes	378
Liquid, ice, or graupel containing multiple randomly-spaced BC inclusions in each bin (DEMA approximation)	2004	J06a	Yes	379
Liquid, ice, or graupel containing multiple randomly-spaced BC, tar ball, and/or soil dust inclusions in each bin	2011	J12b	Yes	380
Solve spectral radiative transfer through DSCRHP	2000	J02a, J10c	Yes	381
Solve spectral radiation transfer through DSCRHP containing multiple or individual BC inclusions (Cloud Absorption Effect I)	2004	J06a	Yes	382
Solve spectral radiation transfer through DSCRHP containing multiple or individual tar ball and/or soil dust inclusions	2011	J12b	Yes	383
Solve spectral radiative transfer through DSCRAP in a cloud	2000	J02a, J10c	Yes	384
Determine LWC for interstitial DSCRAP at relative humidity of cloud to ensure correct coating of water on DSCRAP	2011	J12b	Yes	385
Solve spectral radiative transfer through DSCRAP in a cloud with aerosol LWC determined at the relative humidity of the cloud (Cloud Absorption Effect II)	2011	J12b	Yes	386
Solve spectral radiation transfer through DSCRHP containing multiple or individual BC inclusions and through interstitial DSCRAP simultaneously at the RH of the clear sky	2004	J06a, J10c	Yes	387
Solve spectral radiation transfer through DSCRHP containing multiple or individual BC inclusions and through interstitial DSCRAP simultaneously at the RH of the cloud	2011	J12b	Yes	388
Solve radiative transfer three times each model time step for unresolved clouds; the first two times to determine the temperature change of the clouds due to absorbing inclusions and interstitial aerosol particles, and the third to determine the final radiative properties of the modified clouds	2011	J12b	Yes	389
Solve for cloud drop or ice crystal shrinkage or growth during a time step due to cloud heating/cooling during the step by absorbing inclusions and interstitial aerosol particles	2011	J12b	Yes	390
Calculate BC aerosol mass absorption coefficient online throughout model domain for both externally- and internally-mixed BC during the same simulation, accounting for BC aging.	2011	J12b	Yes	391
Calculate BC hydrometeor mass absorption coefficient online throughout model domain.	2011	J12b	Yes	392
Ice crystals/graupel shape approximated as collection of spheres of equivalent volume:area ratio and total volume for Mie calculations	2004	J05f	Yes	393

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	394
UV/Visible gas absorption				
Spectral absorption cross sections of all photolyzing gases for heating	1990	J94c, J96b	Yes	395
Temperature-dependence of absorption cross sections for heating	1993	J94c, J96b	Yes	396
Spectral UV/visible absorption by nitrated aromatic gases	1997	J99a	Yes	397
Spectral quantum yields of all photolysis processes	1990	J94c, J96b	No	
For use in coupled air quality-meteorological model	1993	J94c, J96b	Yes	398
Temperature-dependence of quantum yields	1993	J94c, J96b	Yes	399
Solar-IR, thermal-IR gas absorption				
Spectral absorption coefficients from T89 in 3-D	1990	J94c, J96b	Yes	400
H_2O, CO_2, CH_4, O_3, O_2	1990	J94c, J96b	Yes	401
Spectral absorption coefficients from M97 in 3-D	1996	J98b	Yes	402
H_2O,CO_2,CH_4,O_3,N_2O,CH_3Cl,$CFCl_3$,CF_2Cl_2,CCl_4	1996	J98b	Yes	403
Multiple absorber method	2001	J05b	Yes	404
Spectral absorption coefs. parameterized from HITRAN data	2001	J05b	Yes	405
Method accounts for multiple absorbing gases simultaneously	2001	J05b	Yes	406
H_2O,CO_2,CH_4,CO,O_3,O_2,N_2O,CH_3Cl,$CFCl_3$,CF_2Cl_2,CCl_4	2001	J05b	Yes	407
Function of temperature, pressure, mixing ratio	2001	J05b	Yes	408
Currently 592 solar-IR and thermal-IR wavelengths and probability intervals in each grid cell	2001	J04d, J05b	Yes	409
Spectral surface albedos / emissivities				
Snow / sea ice albedo / emissivity predicted	2002	J04d	Yes	410
Rad. transfer solved through many air layers, one snow or ice layer	2002	J04d	Yes	411
Albedo, emissivity = upward/downward irradiance above snow or ice	2002	J04d	Yes	412
Accounts for absorption by BC in snow/ice from dry deposition	2002	J04d	Yes	413
Accounts for absorption by BC in snow/ice from precipitation	2002	J04d	Yes	414
Accounts for absorption by soildust in snow/ice from dry deposition	2006	J07c	Yes	415
Accounts for absorption by soildust in snow/ice from precipitation	2006	J07c	Yes	416
Accounts for absorption by tar balls in snow/ice from dry deposition	2011	J12b	Yes	417
Accounts for absorption by tar balls in snow/ice from precipitation	2011	J12b	Yes	418
Prognostic equation for change in snow particle radius due to aging	2010	J12a	No	419
Online spectral radiative calculation through snow layer for albedo accounts for snow aging	2010	J12a	Yes	420
Prognostic equation for concentration of chemicals in snow	2006	J07c	Yes	421
Accounts for precipitation and dry deposition source	2006	J07c	Yes	422
Accounts for burial and sinking of chemicals through snow	2002	J04d	Yes	423
Ocean water albedos/emissivities predicted	2003	J07a	Yes	424
Refractive index of ocean water a function of composition	2003	J07a	Yes	425
Accounts for optical properties size-resolved phytoplankton in ocean	2010	J10c	Yes	426
Other surfaces, albedos/emissivities from 1-km data	1999	J01d	No	
Daily variation of Earth-sun distance for spectral radiative transfer	1990	J99d, J05d	Yes	427
Zenith angle affected by space-atm. refraction for spectral rad, transfer	2002	J04d	Yes	428
Topographical shading for spectral radiative transfer	2000	J04d	Yes	429
Separate column spectral radiative transfer calc. for clear/cloudy sky	2000	J02b	Yes	430
Results weighed by cloud fraction to obtain grid-cell averaged spectral irradiances, actinic fluxes	2000	J02b	Yes	431

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	432
Fractions of each class determined from soil, landuse data	1999	J01c	Yes	433
Vegetation fraction over each subgrid soil class in each grid cell	1999	J01c	Yes	434
Determined from landuse, vegetation data	1999	J01c	Yes	435
Landuse data				
Provides canopy height over each subgrid soil class in each cell	1999	J01c	Yes	436
Provides road/rooftop fraction in each cell	1999	J01c	Yes	437
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	438
Determination of albedo of agricultural versus nonagricultural land from agricultural fraction and observed albedo of mixed pixel	2006	J08b	Yes	439
LAI in each subgrid soil class is found by combining vegetation 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	440
Treats daily irrigation in each grid cell for California	2006	J08b	Yes	441
Treatment of subgrid roof and road surfaces at actual size in global model	2001	J01c	Yes	442
Climate response of subgrid roof and road surfaces in global model	2011	J12a	Yes	443
Climate response of subgrid white roofs in global model	2011	J12a	Yes	444
Equations developed to solve subgrid snow depth	1999	J01c	Yes	445
Snow depth increases due to precipitation of size-resolved ice and graupel and due to vapor deposition at surface	1999	J01c, J03	Yes	446
Snow depth decreases due to melting at top or bottom of snow layer and sublimation at top of snow layer	1999	J01c, J04d	Yes	447
Snow converts to sea ice when the weight of snow plus ice submerges part of the snow below water.	2010	J12a	No	
Snow density varies with depth	2010	J12a	No	
Heat conduction through snow accounts for the continuous variation of thermal conductivity with snow density and depth	2010	J12a	Yes	448
Equations developed to solve subgrid sea ice depth	1999	J01c	Yes	449
Sea ice depth increases due to precip. of size-resolved ice, graupel, vapor deposition at surface	1999	J01c, J03	Yes	450
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	451
Sea ice horizontal velocities are calculated as a function of air and ocean water velocities and drag coefficients.	2012		No	
Sea ice is advected horizontally with calculated sea ice velocities	2012		No	
Equations developed to solve surface/soil temperature/moisture over				
Subgrid soil covered with vegetation	1999	J01c	Yes	452
Calculates temp/moisture of foliage, air in foliage, ground iteratively	1999	J01c	Yes	453
Calculates soil temperature/moisture below subgrid surface over time	1999	J01c	Yes	454
Subgrid soil covered with snow over vegetation	1999	J01c	Yes	455
Subgrid bare soil covered with snow	1999	J01c	Yes	456
Subgrid roads	1999	J01c	Yes	457
Accounts for conduction between road surface and soil below	1999	J01c	Yes	458
Accounts for dew/rain accumulation/runoff on road surfaces	1999	J01c	Yes	459
Subgrid rooftops	1999	J01c	Yes	460
Account for multiple layers of different roofing material on each roof	1999	J01c	Yes	461
Account for conduction between rooftop and air below roof	1999	J01c	Yes	462
Account for dew/rain accumulation/runoff on roof	1999	J01c	Yes	463

Subgrid roads/rooftops covered with snow	1999	J01c	Yes	464
Subgrid water bodies	1999	J01c	Yes	465
Subgrid water bodies covered with sea ice	1999	J01c	Yes	466
Subgrid water bodies covered with snow over sea ice	1999	J01c	Yes	467
Grid-scale radiative, latent heat, sensible heat fluxes calculated from subgrid fluxes, weighted by subgrid surface class fraction	1999	J01c	Yes	468
Energy release during biomass burning added to the thermodynamic energy equation in each surface grid cell where burning occurs.	2006	J09, J10c	Yes	469
Energy release during biofuel burning added to the thermodynamic energy equation in each surface grid cell where burning occurs.	2010	J12d	Yes	470
Energy release during thermal power plant combustion used to evaporate cooling water and remainder is used in the thermodynamic energy equation in each surface grid cell where combustion occurs.	2010	J12d	Yes	471
Energy release during vehicle combustion used in the thermodynamic energy equation in each surface grid cell where combustion occurs.	2010	J12d	No	
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	472
Ocean-atmosphere exchange solved for all atmospheric gases between each top water layer and the air	2004	J05c	Yes	473
Vertical diffusion of all chemicals solved in all subsurface water layers	2004	J05c	Yes	474
2-D ocean dynamics is solved globally in the surface mixed layer	2001	K09, J02b	No	
Vertical diffusion of energy solved in all subsurface water layers	2004	J07d	No	
CO_2 chemical weathering loss at ocean bottom	2008	J10a, J10c	No	
3-D Ocean equilibrium chemistry				
EQUISOLV O solver	2004	J05c	Yes	475
Conserves moles, charge, unconditionally stable, positive-definite	2004	J05c	Yes	476
Solves any number of ion-liquid-solid equilibrium equations	2004	J05c	Yes	477
Now: Na-Cl-Mg-Ca-K-H-O-Li-Sr-C-S-N-Br-F-B-Si-P system	2004	J05c	Yes	478
Accounts for nonideality of ocean solutions	2004	J05c	Yes	479
Solves ocean ionic and molecular composition, including carbon	2004	J05c	Yes	480
Used to determine composition of sea spray emissions	2007	J09	Yes	481
Solves ocean pH, salinity, alkalinity, density, ionic strength	2004	J05c	Yes	482
Ocean-atmosphere exchange				
OPD (Ocean Predictor of Dissolution) solver	2004	J05c	Yes	483
Transfers all model gases between atmosphere and ocean	2004	J05c	Yes	484
Accounts for current ocean composition from EQUISOLV O	2004	J05c	Yes	485
Noniterative, conserves moles, unconditionally stable, pos.-definite	2004	J05c	Yes	486
2-D ocean dynamics scheme of K09				
Predicts velocities, mixed-layer depths, temperatures in online coupled air quality-meteorological-ocean model	2001	K09, J02b	Yes	487
Conserves potential enstrophy in frictionless, barotropic flow limit	2001	K09, J02b	Yes	488
Conserves total energy for frictionless, adiabatic flow	2001	K09, J02b	Yes	489
Conserves potential enthalpy for adiabatic flow and mass	2001	K09, J02b	Yes	490
Ocean temperatures feed back to spectral radiative transfer	2001	J02b	Yes	491
Ocean temperatures feed back to sea ice depth	2001	J02b	No	
Ocean temperatures feed back to ocean composition in online coupled	2004	J05c	Yes	492

air quality-meteorological-ocean model				
Ocean temperatures feed back to ocean/atmosphere exchange	2004	J05c	Yes	493
Ocean temperatures feed back to ocean albedo, emissivities	2003	J07a	Yes	494
Vertical diffusion of energy / chemicals to deep ocean				
10 layers below the all ocean grid cell surfaces	2004	J05c	No	
Unconditionally stable 2nd-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	495
Health effects				
Calculation of the health impacts of ozone particulate matter, and carcinogenic air pollutants online from time-varying gridded concentrations in the model.	2010	J10a	Yes	496
Calculation of the health impacts of radionuclides from time-varying gridded modeled concentrations, country-specific age distributions, and organ-specific relative risks.	2011	T12	Yes	497

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
LWC = liquid water content
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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