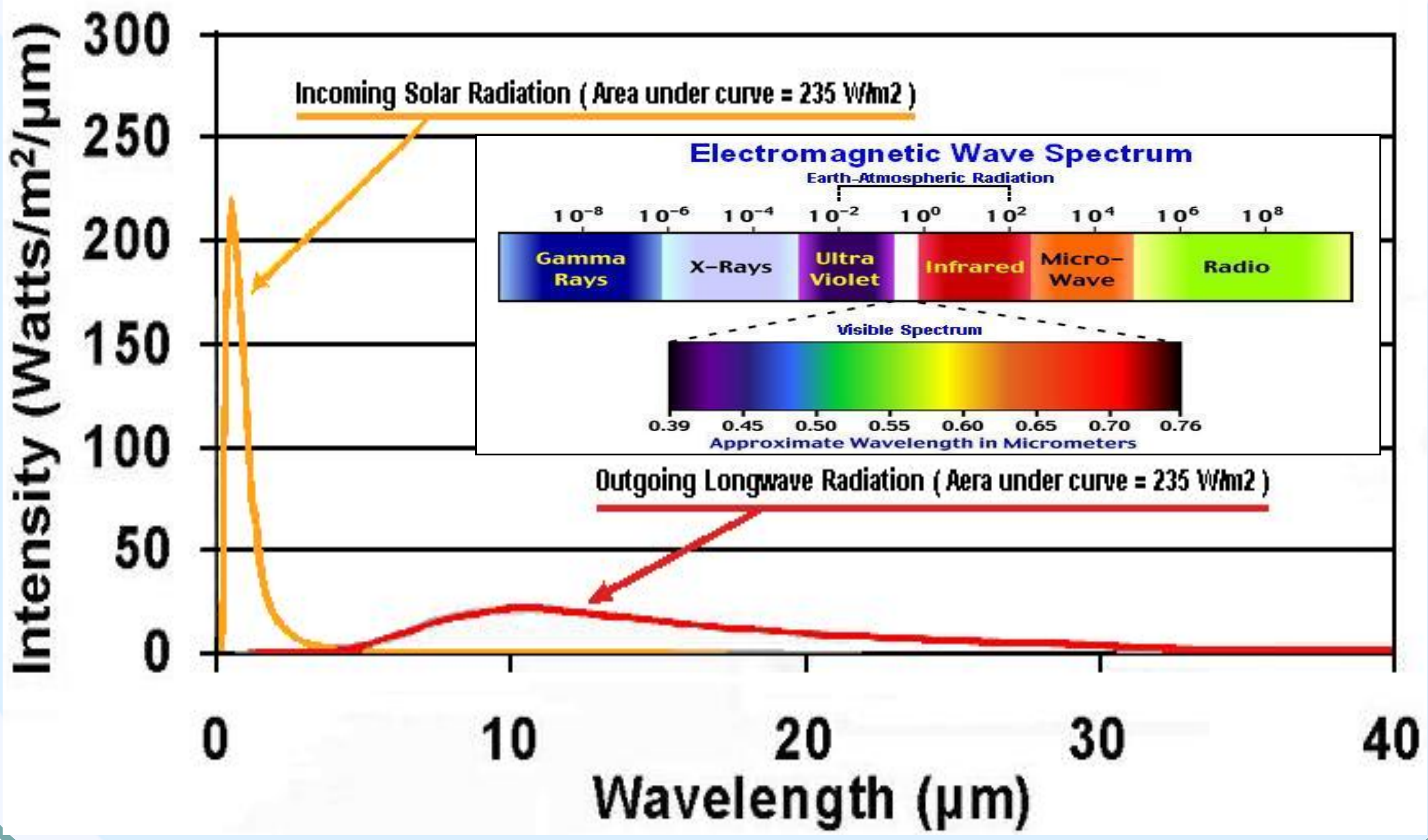
Representation of Radiation and Stratospheric Ozone/H_2O Physics in FV^3GFS

Most of the radiation slides are prepared by Dr. Yu-Tai Hou of EMC

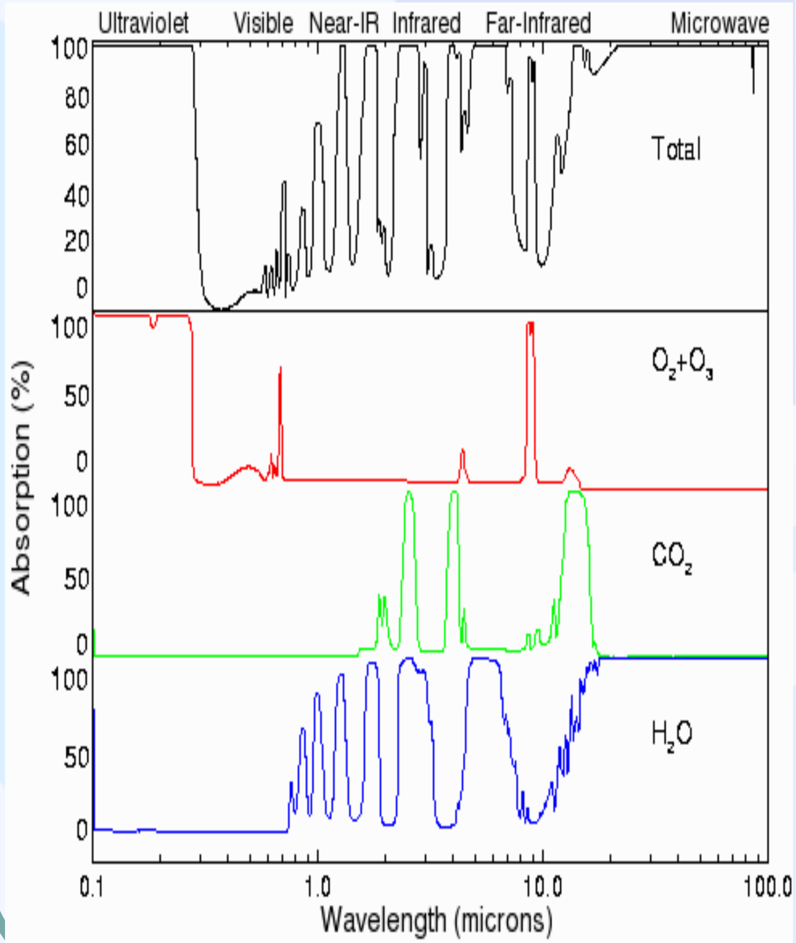
Modeling of Atmospheric Radiative Processes

- Radiative processes in the Earth System are very complex
- Energy input to this system is through solar radiation at the top of the atmosphere
- Energy loss from the system is primarily via IR cooling to space at the top of the atmosphere.
- Fortunately for life, the balance between this incoming and outgoing radiation puts Earth System in the "Goldielocks" zone.
- However, such equilibrium is achieved through complex radiative transfer in the atmosphere and the resulting heat and energy transfer in the Earth System
- Accurate modeling of atmospheric radiative processes is very important for all Earth System Models, including NWP and Climate models, but can be computationally intensive.

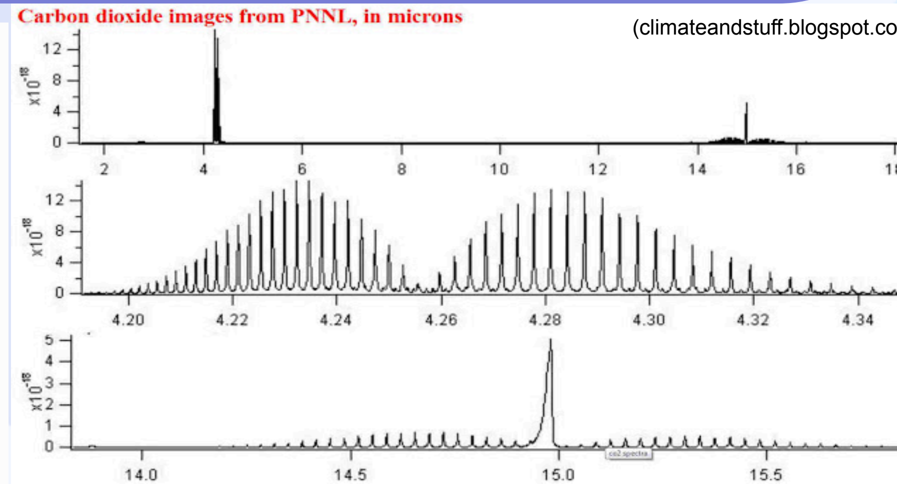
Atmospheric Radiative Energy Spectral Distributions



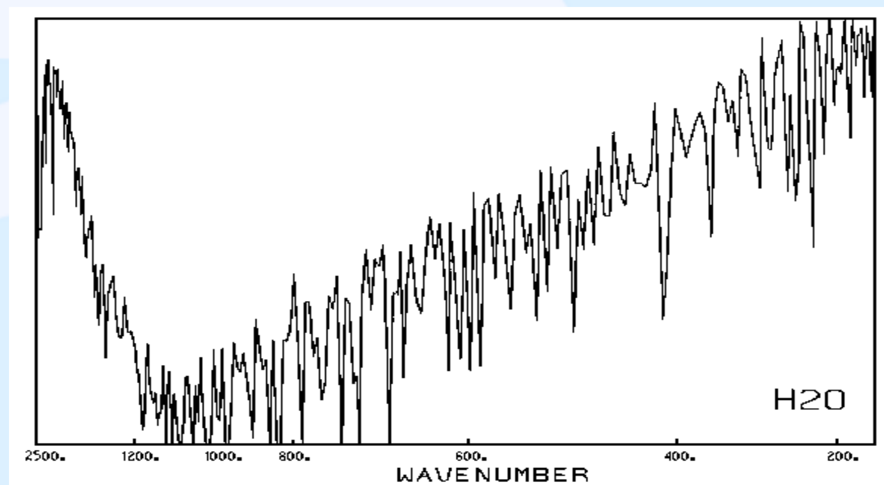
Atmospheric Absorptions



(wattsupwiththat.com)

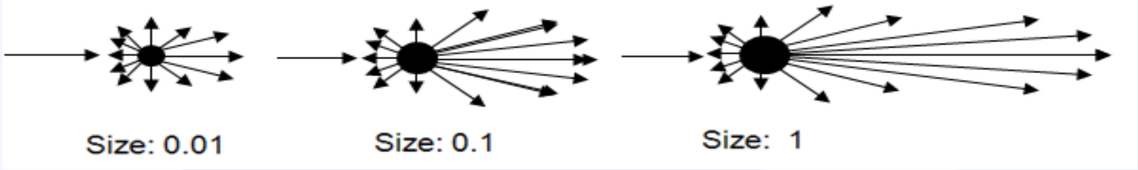


(climateandstuff.blogspot.com)



Atmospheric Scatterings

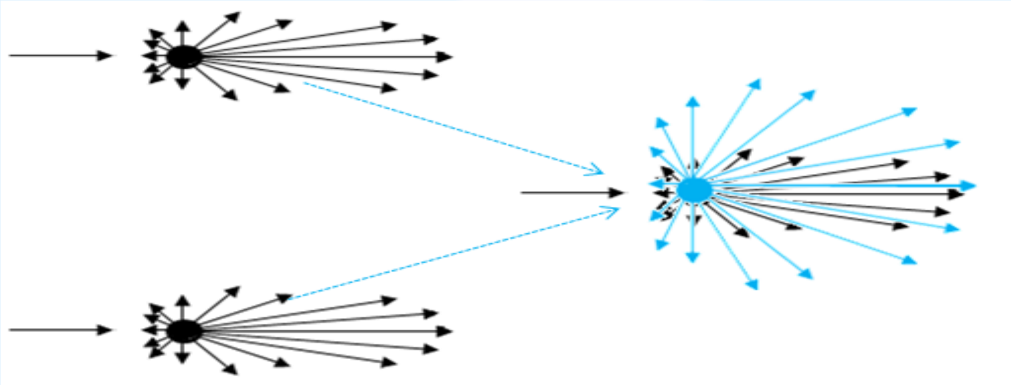
- Relative particle sizes to the wavelength (Rayleigh or Mie scatterings)



- Multi-scatterings complicate the calculation

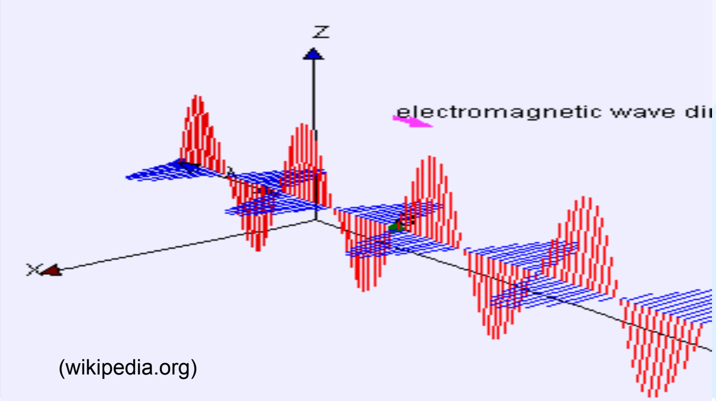
General expression of the phase function (Legendre expansion)

$$P(\mu) = \sum_{j=0}^{\infty} [(2m+1)\, q^{J}]\, L_j(\mu)$$



Radiative Transfer in the Earth-Atmosphere System

Simplified radiative transfer equations:
- monochromatic, 1-D, plane-parallel, local-thermodynamic-equilibrium, azimuthally independent,…



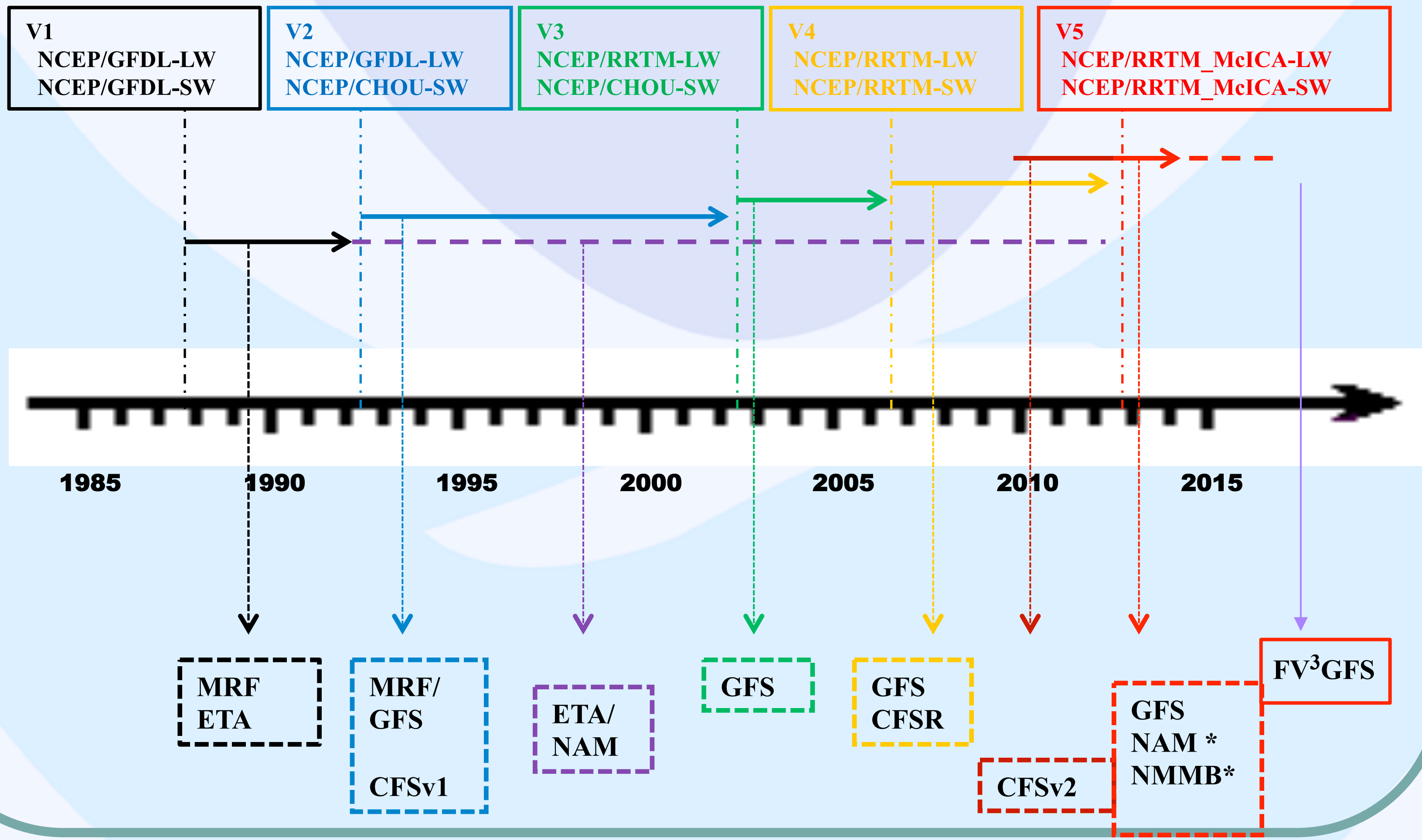
(wikipedia.org)

$$\mu\frac{\partial I}{\partial \tau}(\tau,\mu) = I(\tau,\mu) - S(\tau) \;:\qquad \mu = \cos(\theta);\quad \tau(s) = e^{-\int k ds};$$

$$S(\tau) = [1-\alpha(\tau)]\,\mathbf{B}(\tau) + \frac{1}{2}\int_{-1}^{1} I(\tau,\mu)P(\mu,\mu')\,d\mu + [\text{inhomogeneous terms}]$$

The integral-differential equation needs further simplifications for practical NWP applications:
- non-scattering (LW), non-emission (SW), how about transition region
- parameterized band models validated by LBL models
- pre-computed transmission tables, k-distribution, …
- discrete-ordinate, single, two or multi-stream method, …

History of Radiation Parameterization Development at NCEP



NCEP Unified Radiation Module Structures

Features:

Standardized component modules, General plug-compatible, Simple to use, Easy to upgrade, Efficient, and Flexible for future expansion

1. **Driver module** - prepares astronomy parameters, atmospheric profiles (aerosols, gases, clouds), and surface conditions
2. **Astronomy module** - obtains astronomic parameters, local solar zenith angles.
3. **Aerosol module** - establishes aerosol profiles and optical properties
4. **Gas module** - sets up absorbing gas profiles (O_3, CO_2, rare gases, …)
5. **Cloud module** - prepares cloud profiles (cloud frac, condensate path, eff radius,…)
6. **Surface module** - sets up surface albedo and emissivity
7. **SW radiation module** - computes SW fluxes and heating rates (contains three separate parts: **parameters**, **data tables**, and **main program**)
8. **LW radiation module** - computes LW fluxes and heating rates (contains three separate parts: **parameters**, **data tables**, and **main program**)

Schematic Structure Diagram

Driver Module
- init / update
- main driver

Astronomy Module
- init / update
- astronomy params
- mean coszen

Gases Module
- init / update
- O_3
- CO_2
- rare gases

Cloud Module
- Init / update
- prognostic cld-1
- prognostic cld-2

Aerosol Module
- init / update
- clim aerosols
- GOCART aerosols

Derived Type :
aerosol_type

Surface Module
- initialization
- SW albedo
- LW emissivity

Derived Type :
sfcalb_type

SW Param Module

SW Data Table Module

SW Main Module
- initialization
- sw radiation

Outputs :
total sky heating rates
surface fluxes (up/down)
toa atms fluxes (up/down)

Optional outputs:
clear sky heating rates
spectral band heating rates
fluxes profiles (up/down)
surface flux components

LW Param Module

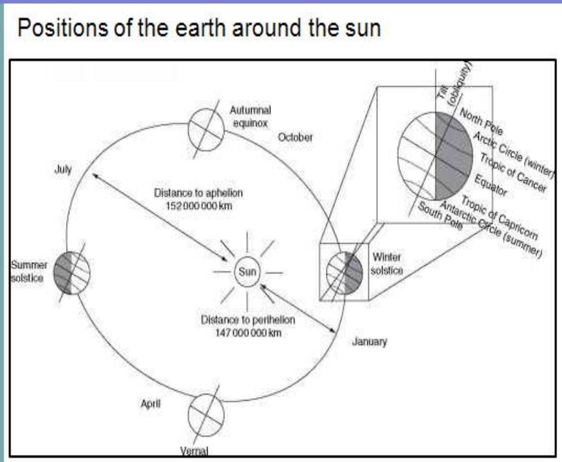
LW Data Table Module

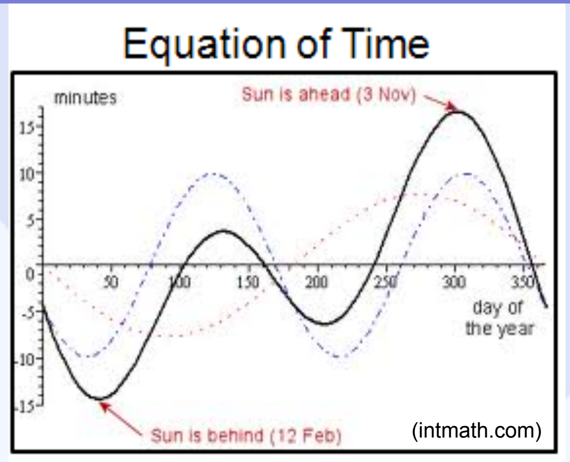
LW Main Module
- initialization
- lw radiation

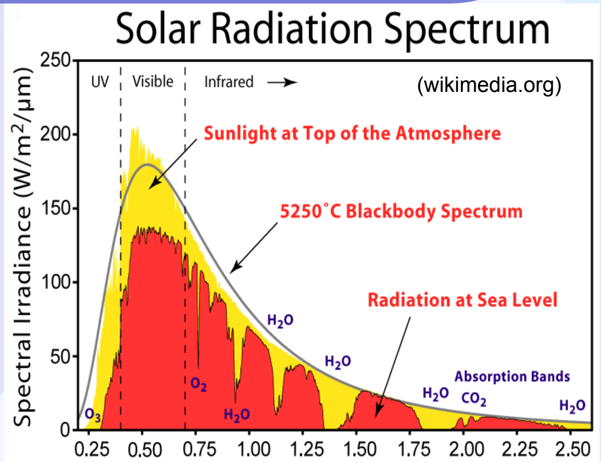
Outputs :
total sky heating rates
surface fluxes (up/down)
toa atms fluxes (up/down)

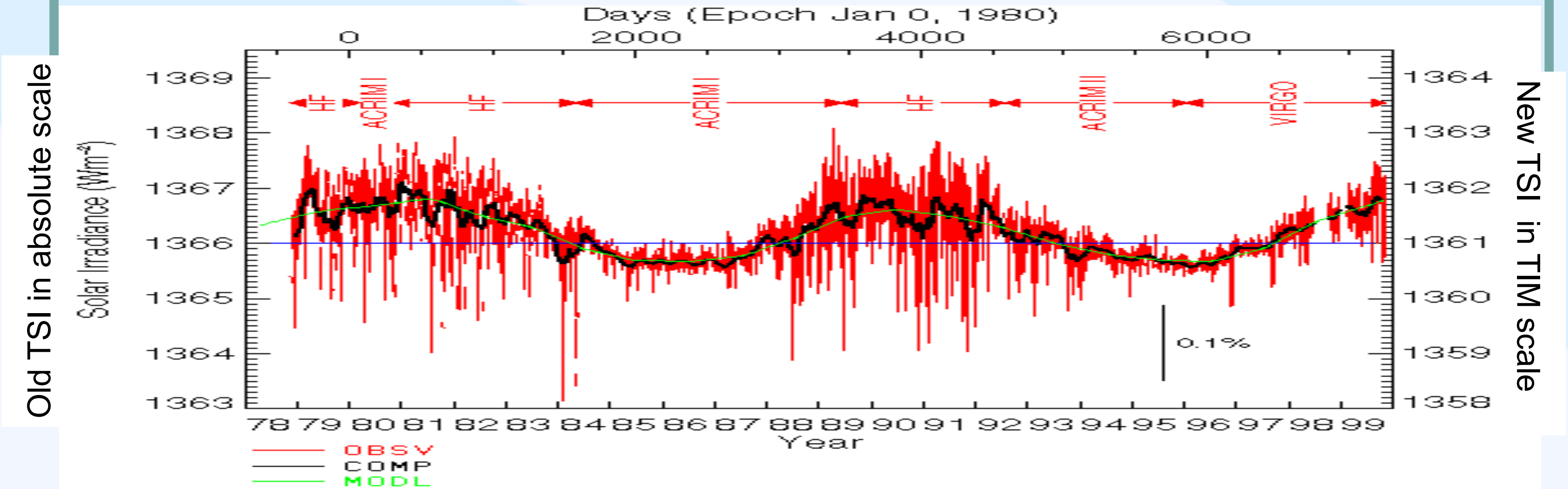
Optional outputs:
clear sky heating rates
spectral band heating rates
fluxes profiles (up/down)

Radiation_Astronomy Module









Radiation_Astronomy Module

Model selections for Solar constant value :

(namelist control parameter – **ISOL** **RADv5 features in blue**)

ISOL=0: prescribed value = 1366 w/m2 (old)

ISOL=10:prescribed value = 1361 w/m2 (new)

ISOL=1: NOAA old yearly solar constant table with 11-year cycle (range:1944-2006)

ISOL=2: NOAA new yearly solar constant table with 11-year cycle (range:1850-2019)

ISOL=3: CMIP5 yearly solar constant table with 11-year cycle (range:1610-2008)

ISOL=4: CMIP5 monthly solar constant table with 11-year cycle (range1882-2008)

Radiation_aerosols Module

Aerosol distribution: (namelist control parameter – **IAER**; **IAER_MDL**)

IAER_MDL=0: OPAC-climatology tropospheric model (monthly mean,15° horizontal resolution)

IAER_MDL=1: GOCART-climatology tropospheric aerosol model

IAER_MDL=2: GOCART-climatology prognostic aerosol model

Stratosphere: historical recorded volcanic forcing in four zonal mean bands (1850-2000)

IAER = abc of 3-digit integer flags: a-volcanic, b-LW, c-SW

- a=0: include background stratospheric volcanic aerosol effect (if both b & c /=0)
- a=1: include recorded stratospheric volcanic aerosol effect
- b=0: no LW tropospheric aerosol effect
- b=1: include LW tropospheric aerosol effect
- c=0: no SW tropospheric aerosol effect
- c=1: include SW tropospheric aerosol effect

Radiation_Gases Module

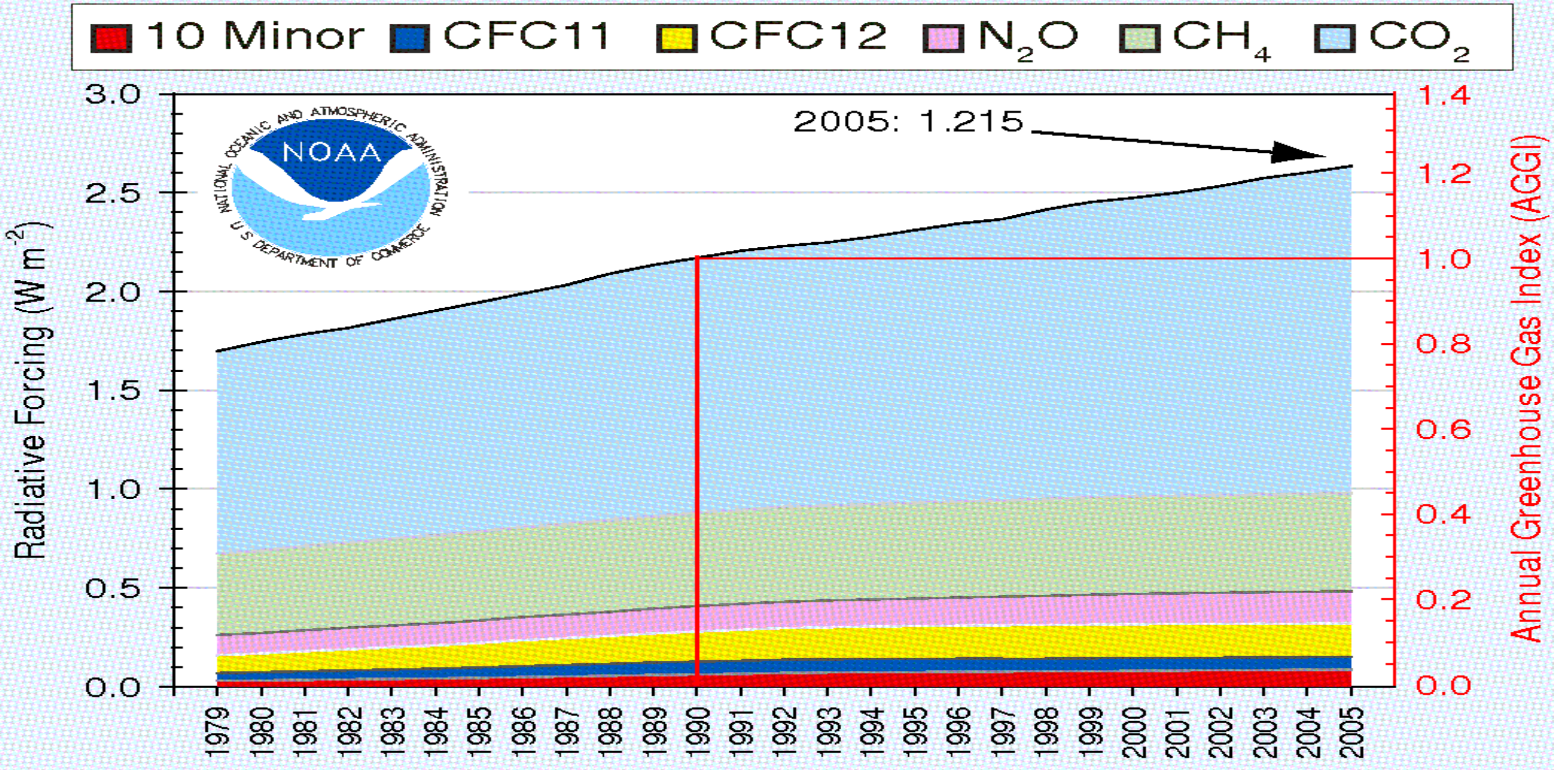


Figure 2. Changes in atmospheric radiative forcing by long-lived greenhouse gases and the 2005 NOAA Annual Greenhouse Gas Index (AGGI).

WMO Annual Greenhouse Gas Bulletins (2005)

Radiation_Gases Module

CO_2 Distribution : (namelist control parameter - **ICO2)**

ICO2 = 0 : use prescribed global annual mean value (currently=380 ppmv)

ICO2 = 1 : use observed global annual mean value

ICO2 = 2 : use observed monthly 2-d data table in 15° horizontal resolution

O_3 Distribution : (namelist control parameter – **NTOZ)**

NTOZ = 0 : use seasonal and zonal averaged climatological ozone

NTOZ > 0 : use 3-D prognostic ozone

Trace Gases : (currently using the global mean climatology in unit of ppmv**)**

CH_4 - 1.50×10^{-6}	N_2O - 0.31×10^{-6}	O_2 - 0.209
CO - 1.50×10^{-8}	CF11 - 3.52×10^{-10}	CF12 - 6.36×10^{-10}
CF22 - 1.50×10^{-10}	CF113 - 0.82×10^{-10}	CCL4 - 1.40×10^{-10}

Radiation_Clouds Module

Cloud prediction model: (namelist control parameter – **NTCW, IMP_PHYSICS)**

NTCW = 0 : legacy diagnostic cloud scheme based on RH-table lookup table

NTCW > 0 : prognostic cloud condensate

IMP_PHYSICS = 98/99 : Zhao-Carr-Sundqvist MP – Xu-Randall diagnostic cloud fraction

IMP_PHYSICS = 11 : GFDL MP – unified diagnostic cloud fraction provided by GFDL MP

Cloud overlapping method: (namelist control parameter – **IOVR_LW, IOVR_SW)**

IOVR = 0 : randomly overlapping vertical cloud layers

IOVR = 1 : maximum-random overlapping vertical cloud layers

Sub-grid cloud approximation: (namelist control parameter – **ISUBC_LW, ISUBC_SW)**

ISUBC = 0 : grid averaged quantities, without sub-grid cloud approximation

ISUBC = 1 : with McICA sub-grid approximation (use prescribed permutation seeds)

ISUBC = 2 : with McICA sub-grid approximation (use random permutation seeds)

Other relevant logical namelist control flags: (covered in other physics topics)

crick_proof; ccnorm; norad_precip; etc.

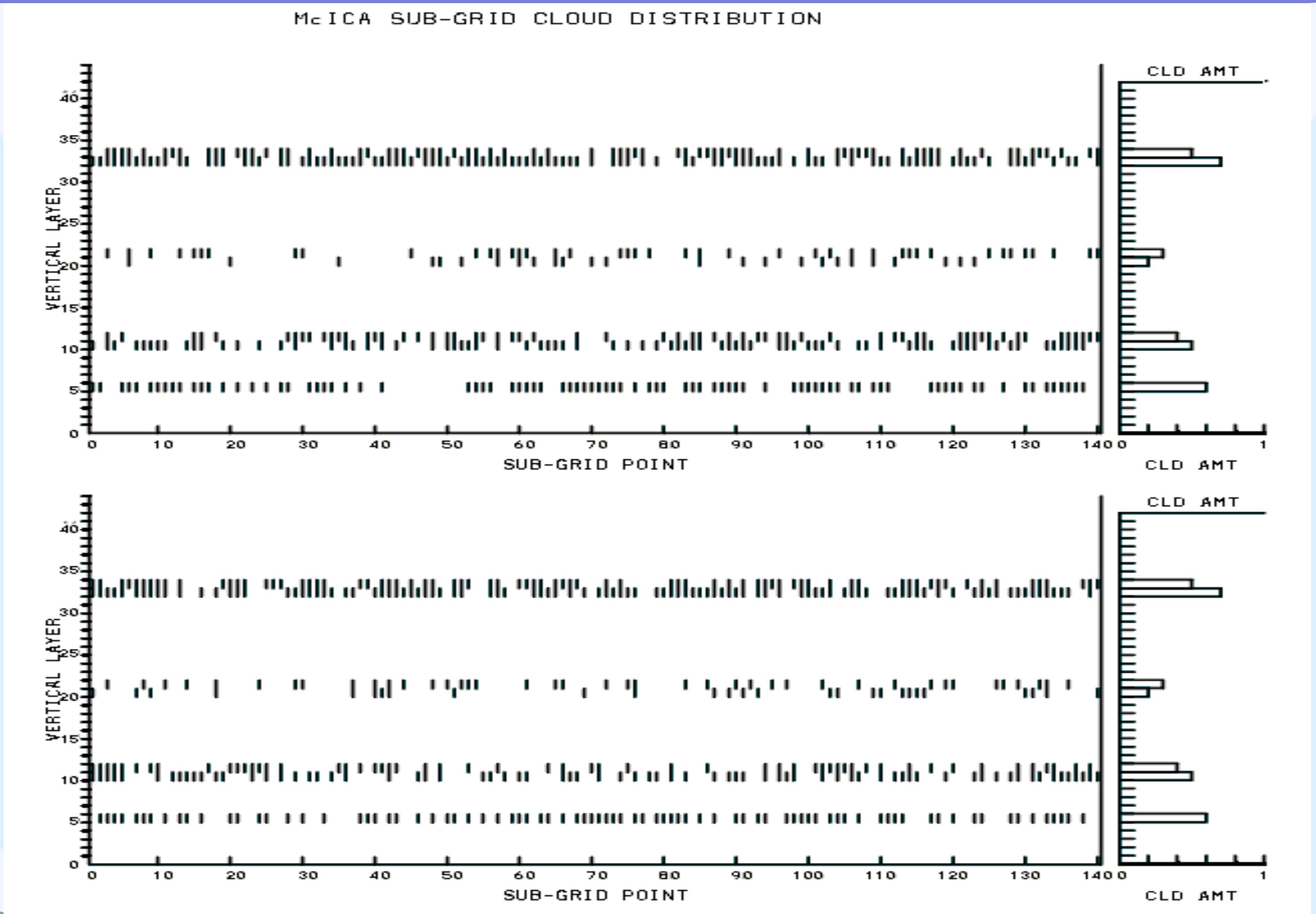
Difficulty in presenting clouds for radiation computations:

- Clouds highly inhomogeneous both space and time
- Complexity of cloud condensates (gas/liquid/ice/snow/rain …) produce a wide range of radiative spectral responses.
- Even at very high resolution, it is hardly possible to capture the details of the complexity and randomness of cloud structure and distribution.

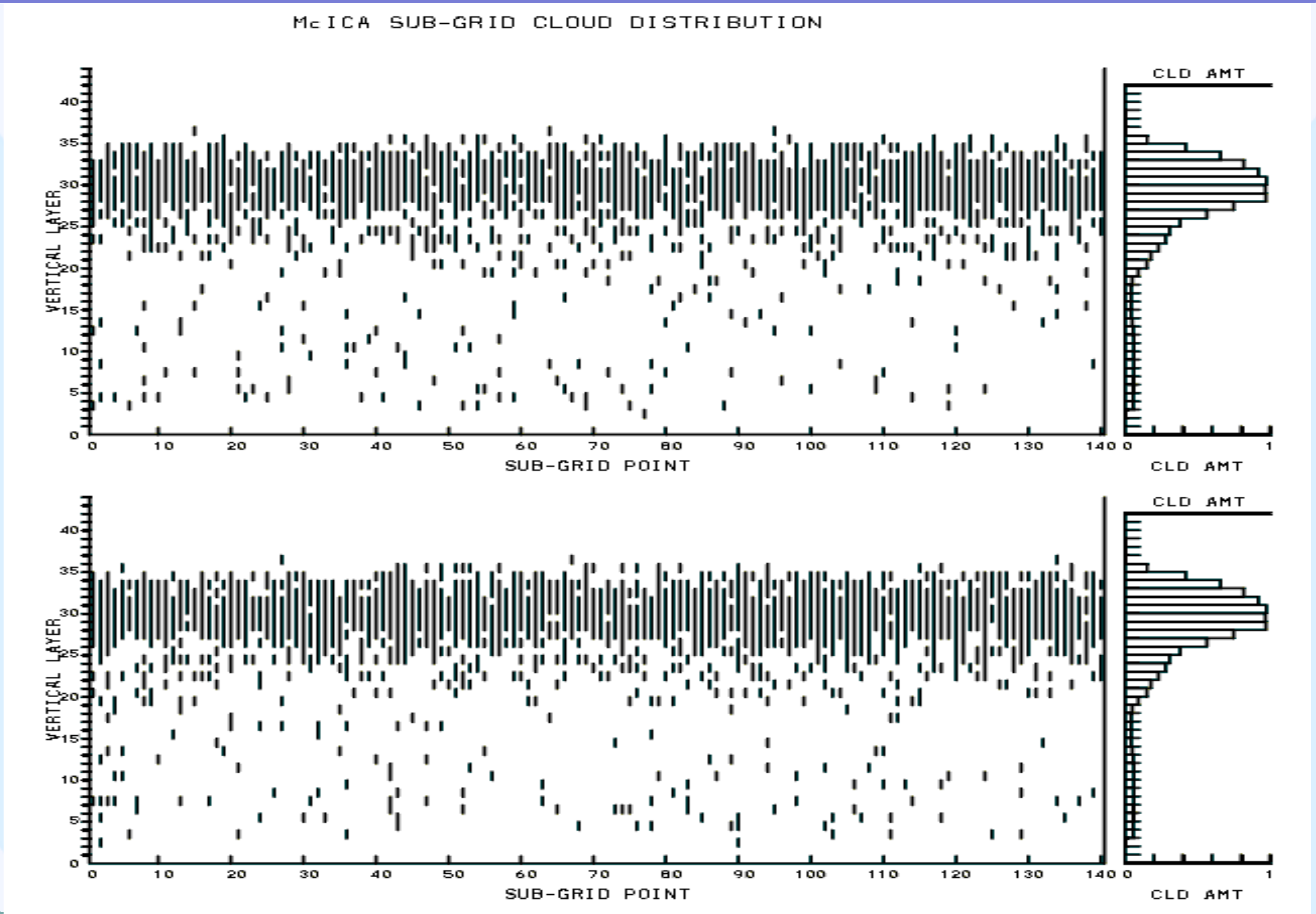
Resolving sub-grid structures

- **Nested 2-D cloud resolving model (CRM) – O(N)** very expansive, (N: number of sub-grid profiles, full RT computation for each sub-grid profile)
- **Independent column approximation (ICA) – O(N)** very expensive, (N: number of sub-grids, full RT computation for each sub-grid)
- **Monte-Carlo independent column approximation (McICA) – O(~1)** considerably less expensive (partial RT for each sub-grid)

Examples of ICA-distribution of vertical randomly overlapped thin layered clouds:



Examples of ICA-distribution of vertical max-randomly overlapped thick layered clouds:



McICA sub-grid cloud approximation

General expression of 1-D radiation flux calculation:

$$\mathcal{F} = \sum_{k=1}^{\mathcal{K}} F_k$$

where F_k are spectral corresponding fluxes, and the total number, K, depends on different RT schemes

Independent column approximation (ICA):

$$\langle F \rangle = \frac{1}{\mathcal{N}} \sum_{n=1}^{\mathcal{N}} \mathcal{F}_n$$

where N is the number of total sub-columns in each model grid

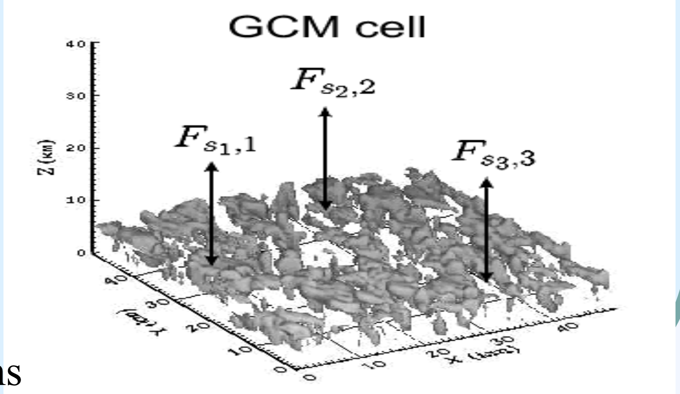
That leads to a double summation:

$$\langle \mathcal{F} \rangle = \frac{1}{\mathcal{N}} \sum_{n=1}^{\mathcal{N}} \sum_{k=1}^{\mathcal{K}} F_{n,k}$$

that is too expensive for most applications!

Monte-Carlo independent column approximation (McICA):

In a correlated-k distribution (CKD) approach, if the number of quadrature points (g-points) are sufficient large and evenly treated, then one may apply the McICA to reduce computation time.



$$\langle \mathcal{F} \rangle = \frac{1}{\mathcal{N}} \sum_{n=1}^{\mathcal{N}} \sum_{k=1}^{\mathcal{K}} F_{n,k} \approx \langle \mathcal{F} \rangle = \sum_{k=1}^{\mathcal{K}} F_{s_k,k}$$

Here k is the number of randomly generated sub-columns

Advantages of McICA

- One efficient way to mimic the random nature of cloud distributions. May also be useful for ensemble applications.
- A complete separation of optical characteristics from RT solver and has been shown to be unbiased against ICA (Barker et al. 2002, Barker and Raisanen, 2005)
- In addition of cloudiness, the same concept can be used to treat cloud condensate as well.
- Currently implemented in GFS with simple cloud vertical overlapping assumptions (random or maximum-random), more elaborate scheme (e.g. de-correlation length) is under development.
- Shows significant impact on climate-scale, moderate impact on medium to short-range forecast (infrequent interactions)

Radiation_surface Module

SW:

$$F_{net} = F^{\downarrow} - F^{\uparrow} = \sum_{\nu}[1 - \alpha_{\nu,dir}(\mu)]\, F^{\downarrow}_{\nu,dir} + \sum_{\nu}[1 - \alpha_{\nu,dif}]\, F^{\downarrow}_{\nu,dif}$$

LW:

$$F_{net} = F^{\uparrow} - F^{\downarrow} = \sum_{\nu}[\varepsilon_{\nu}\, F^{\uparrow}_{\nu}(T_s) + (1 - \varepsilon_{\nu})\, F^{\downarrow}_{\nu}(T_a)] - \sum_{\nu} F^{\downarrow}_{\nu}(T_a) = \sum_{\nu} \varepsilon_{\nu}[\sigma T_s^4 - F^{\downarrow}_{\nu}(T_a)]$$

SW surface albedo: (namelist control parameter - **IALB**)

IALB=0: surface vegetation type based climatology scheme (monthly data in 1° horizontal resolution)

IALB=1: MODIS retrievals based monthly mean climatology

LW surface emissivity: (namelist control parameter - **IEMS**)

IEMS=0: black-body emissivity (=1.0)

IEMS=1: surface type based climatology in 1° horizontal resolution

LW Radiation parameter Modules - 1

LW radiation contains the following modules:

radlw_parameters : define spectral ranges, type parameters, etc.

radlw_cntr_para : define pre-compilation control parameters

(in radiation v5, control parameters in this module are relocated to a general accessible module, "physpara")

Pre-Compilation control parameter settings:

ilwrate - define the unit used for output of LW heating rates

=1: LW heating rate output in k/day; =2: output in k/second

irgaslw - define rare gases (ch4,n2o,o2…) effect in LW computation

=0: no rare gases effect in LW; =1: include rare gases effects

icfclw - define halocarbon (cfc) gases effect in LW computation

=0: no cfc gases effect in LW; =1: include cfc effects

ilwrgas – in module physpara, combining two rare gases flags

=0: no rare gases effect in LW; =1: include all rare gases effects

LW Radiation parameter Modules - 2

Pre-Compilation control parameter settings (continue):

iaerlw - define spectral property of aerosol used in LW computation
=1: optical properties are spectral dependent; =2: 1 broad band method

lalw1bd - logical flag in module physpara, 1 or multi bands for aerosol prop.
=true: use one broad-band approach; = false: multi-band approach

iflagliq - input method for liquid water clouds
=0: input cloud optical depth, ignor "**iflagice**" setting
=1: input cloud liq and ice paths (ccm2 method) ignore "**iflagice**" setting
=2: input cloud liq path & eff radius (ccm3 method) for water cloud
=3: input cloud liq path & eff radius (Hu&Stamnes 1993) for water cloud

ilwcliq - in module physpara for liquid water clouds
=0: input cloud optical depth, ignore "**ilwcice**" setting
=1: input cloud liq path & eff radius (Hu&Stamnes 1993) for water cloud

iflagice - input method for ice clouds
=0: input cloud ice path & eff radius (ccm3 method) for ice cloud
=1: input cloud ice path & eff radius (Ebert & Curry 1997) for ice cloud
=2: input cloud ice path & eff radius (Streamer 1996) for ice cloud

ilwcice - in module physpara for ice clouds
=0 - 2 are the same as the operational **iflagice** settings
=3: input cloud ice path & eff radius (Fu 1998) for ice cloud

SW Radiation parameter Modules - 1

SW radiation contains the following modules:

radsw_parameters : define spectral ranges, type parameters, etc.

radsw_cntr_para : define pre-compilation control parameters

(in radiation v5, control parameters in this module are relocated to a general accessible module, "physpara")

Pre-Compilation control parameter settings:

iswrate - define the unit used for output of SW heating rates

=1: SW heating rate output in k/day; =2: output in k/second

irgassw - define rare gases (ch4,n2o,o2…) effect in SW computation

=0: no rare gases effect in SW; =1: include rare gases effects

iswrgas - in module physpara

=0: no rare gases effect in SW; =1: include rare gases effects

SW Radiation parameter Modules - 2

Pre-Compilation control parameter settings (continue):

iflagliq - input method for liquid water clouds

=0: input cloud optical depth, ignore "**iflagice**" setting

=1: input cloud liq path & eff radius (Hu&Stamnes 1993) for water cloud

iswcliq - in module physpara for liquid water clouds

=0: input cloud optical depth, ignore "**iswcice**" setting

=1: input cloud liq path & eff radius (Hu&Stamnes 1993) for water cloud

iflagice - input method for ice clouds

=0-2: not used

=3: input cloud ice path & eff radius (Fu 1996) for ice cloud

iswcice - in module physpara for ice clouds

=1: input cloud ice path & eff radius (Ebert&Curry 1992) for ice cloud

=2: input cloud ice path & eff radius (Streamer 2001) for ice cloud

=3: input cloud ice path & eff radius (Fu 1996) for ice cloud

imodsw - method used in 2-stream radiative transfer model

=1: delta-eddington (Joseph, 1976)

=2: pitm method (Zdunkowski, 1980)

=3: discrete ordinates (Liou, 1973)

iswmode - in module physpara, the same definitions as in the operational model

Default setting for major namelist variables:

		Functionality	GFS	CFS	RADv5
1.	ISOL	- solar constant	0	1	2
2.	ICO2	- CO2 distribution	0	2	2
3.	IAER	- aerosol effect	011	111	011
4.	IAER_MDL	- aerosol model selection	*	*	0
5.	IALB	- surface albedo	0	0	0
6.	IEMS	- surface emissivity	1	1	1
7.	NUM_P3D	- cloud microphysics	4	4	4
8.	IOVR_SW	- SW cloud overlapping	1	1	1
9.	IOVR_LW	- LW cloud overlapping	1	1	1
9.	ISUBC_SW	- SW sub-grid cloud	0*	2	2
10.	ISUBC_LW	- LW sub-grid cloud	0*	2	2
11.	ICTM	- initial cond time cntl	0	1	1
12.	FHSWR	- SW calling interval	1 (hr)	1 (hr)	3600 (sec)
13.	FHLWR	- LW calling interval	1 (hr)	1 (hr)	3600 (sec)

* not available for the current operational GFS

Radiative fields from Model outputs (W/m^2):

At surface total sky:

- DLWRFsfc - Downward LW
- DSWRFsfc - Downward SW
- ULWRFsfc - Upward LW
- USWRFsfc - Upward SW
- NBDSFsfc - Near IR beam downward
- NDDSFsfc - Near IR diffuse downward
- VBDSFsfc - UV+Visible beam downward
- VDDSFsfc - UV+Visible diffuse downward
- DUVBsfc - UV-B downward flux

At surface clear sky:

- CSDLFsfc - Downward LW
- CSDSFsfc - Downward SW
- CSULFsfc - Upward LW
- CSUSFsfc - Upward SW
- CDUVBsfc - UV-B downward flux

At TOA total sky:

- DSWRFtoa - Downward SW
- ULWRFtoa - Upward LW
- USWRFtoa - Upward SW

At TOA clear sky:

- CSULFtoa - Upward LW
- CSUSFtoa - Upward SW

Stratospheric Ozone Physics in FV^3GFS

Ozone sources and sinks
(ozphys.f)

- Current OPR version based on Naval Research Laboratory's CHEM2D model - McCormack et al., (2006)
- Monthly and zonal mean ozone production rate and ozone destruction rate per unit ozone mixing ratio were provided by NRL based on CHEM2D model
- Original version of these terms were provided by NASA/DAO based on NASA 2D Chemistry model
- Model can run with both versions (just provide the right input file)

Current Ozone Physics in parallel FV^{3}GFS

Based on the development from Climate Program Office sponsored multi-organization project:

Improving the Prognostic Ozone Parameterization in the NCEP GFS and CFS for Climate Reanalysis and Operational Forecasts

Gilbert P. Compo[1,2], Hai-Tien Lee[3], Sarah Lu[4], Shrinivas Moorthi[4], John P. McCormack[5], Craig Long[3], Prashant D. Sardeshmukh[1,2], Jeffrey S. Whitaker[2]

[1]University of Colorado/CIRES
[2]NOAA Earth System Research Laboratory/Physical Sciences Division
[3]NOAA, National Centers for Environmental Prediction, Climate Prediction Center
[4]NOAA, National Centers for Environmental Prediction, Environmental Modeling Center
[5]Naval Research Laboratory

Ozone Physics in FV^{3}GFS

Naval Research Laboratory CHEM2D Ozone Photochemistry Parameterization (CHEM2D-OPP, *McCormack et al. (2006)*)

CHEM2D-OPP is based on gas-phase chemistry circa 2000.
Same approach as used in ECMWF IFS (*Cariolle and Deque 1986*).
Includes ozone depletion from CFCs.

Net ozone photochemical tendency : functional form of Production *P* minus Loss *L*

$$\frac{d\chi_{O_3}}{dt} = (P-L)\left[\chi_{O_3}, T, c_{O_3}\right]$$

Taylor series expansion with respect to a reference state (denoted by overbar) and linearizing,

$$\frac{\partial\chi}{\partial t}(P-L) = (P-L)_0 + \left.\frac{\partial(P-L)}{\partial\chi_{O3}}\right|_0 \left(\chi_{O3} - \bar{\chi}_{O3}\right) + \left.\frac{\partial(P-L)}{\partial T}\right|_0 \left(T - \bar{T}\right) + \left.\frac{\partial(P-L)}{\partial c_{O3}}\right|_0 \left(c_{O3} - \bar{c}_{O3}\right)$$

χ_{O3} prognostic Ozone mixing ratio
T Temperature
c_{O3} column ozone above

Ozone Physics in FV^3GFS

Partial use of CHEM2D-OPP in the current NCEP Global Forecast System (GFS) atmosphere model (using only first two terms)

$$\frac{\partial \chi}{\partial t}(P-L) = (P-L)_0 + \left.\frac{\partial (P-L)}{\partial \chi_{O3}}\right|_0 \left(\chi_{O3} - \bar{\chi}_{O3}\right)$$

Reference tendency $(P\text{-}L)_0$ and all partial derivatives are computed from odd oxygen ($Ox \equiv O_3 + O$) reaction rates in the CHEM2D photochemical transport model.

CHEM2D is a global model extending from the surface to ~120 km that solves 280 chemical reactions for 100 different species within a transformed Eulerian mean framework with fully interactive radiative heating and dynamics.

χ_{O3}	prognostic Ozone mixing ratio
T	Temperature
c_{O3}	column ozone above

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Stratospheric H_2O Physics

H_2O sources and sinks in the stratosphere/mesosphere (h2ophys.f)

- **This new scheme is based on "*Parameterization of middle atmospheric water vapor photochemistry for high-altitude NWP and data assimilation*" by McCormack et al. (2008), from NRL**
- **Accounts for the altitude, latitude, and seasonal variations in the photochemical sources and sinks of water vapor over the pressure region from 100–0.001hPa (~16–90km altitude)**
- **Monthly and zonal mean H_2O production and loss rates are provided by NRL based on the CHEM2D zonally averaged photochemical-transport model of the middle atmosphere**
- **The scheme mirrors that of ozone, with only production and loss terms.**
- **Logical "H_2O_phys" in the physics namelist can be used to turn this off.**

Representation of Radiation and Stratospheric Ozone/H_2O Physics in FV^3GFS

The End

Thank You