Radiation Parameterization in WRF

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Outline

• Radiation overview and equations
• Necessity of parameterization
• Historical overview
• WRF radiation schemes
  – Longwave
  – Shortwave
• Gallus and Bresch study
• Future developments
Radiation

- Radiation is propagation of energy by electromagnetic (EM) waves.

- Solar radiation is the fundamental energy source for the Earth and atmosphere, the unequal distribution reaching the Earth leads to differential heating and horizontal gradients that in turn drive atmospheric circulations.

Radiative flux
Solar spectral energy curve

Spectral energy curve at sea level and extrapolated outside the atmosphere. Darkened areas represent gaseous absorption in the atmosphere. (From Lacis and Hansen 1974)

Longwave spectral energy curve

Radiation emitted from the Earth and atmosphere is in the “longwave” (LW) or infrared (IR) band, where $\lambda$ varies from 4.0 – 25 $\mu$m.
Blackbody Intensity

A blackbody is a theoretical substance that absorbs and emits the maximum possible intensity of radiant energy at a certain wavelength. This intensity was determined by Max Planck as

\[ B_v(T) = \frac{2\hbar c^2}{\left( e^{\frac{\hbar c}{K_BT}} - 1 \right)} \]

Stefan-Boltzmann law

Integrating over all wavenumbers yields the blackbody flux density given by the Stefan-Boltzmann law

\[ \pi B(T) = \pi \int_0^\infty B_v(T) \, dv = \sigma T^4 \]
Emissivity

Emissivity is given by the ratio of emitted monochromatic intensity to corresponding blackbody radiation

\[ \varepsilon_\lambda = \frac{I_\lambda (\text{emitted})}{B_\lambda (T)} \]

Absorptivity, reflectivity, & transmissivity

Monochromatic absorptivity, reflectivity, and transmissivity are respectively given by

\[ \alpha_\lambda = \frac{I_\lambda (\text{absorbed})}{I_\lambda (\text{incident})}, \quad R_\lambda = \frac{I_\lambda (\text{reflected})}{I_\lambda (\text{incident})}, \quad T_\lambda = \frac{I_\lambda (\text{transmitted})}{I_\lambda (\text{incident})} \]

and related by

\[ \alpha_\lambda + R_\lambda + T_\lambda = 1 \]
Radiative transfer

Radiative transfer (RT) describes the effects of radiation passing through a medium. The change of monochromatic intensity of radiation passing through the atmosphere is given by

\[ dI_\lambda = -I_\lambda \rho r k_\lambda ds \]

Flux density

The mean flux density of radiation reaching the outer atmosphere is \(~1368\) W m\(^{-2}\) and is given by

\[ F_S = \int_{\delta \omega} I_s \cos \theta \, d\omega \]

and passing through a layer as

\[ F_{\nu}^{\uparrow \downarrow} (\tau_{\nu}) = 2\pi \int_{0}^{1} I_{\nu}^{\uparrow \downarrow} (\tau_{\nu}, \mu) \mu \, d\mu \]
Flux transmissivity

The flux transmissivity passing through an atmospheric layer can be formulated as

\[ T_v^f = 2 \int_0^1 e^{-\tau_v/\mu} \mu \, d\mu \]

Necessity of parameterization

- Line-by-line integration of above equations over wavenumber in the IR band is computationally intensive, requiring summation over \( \sim 10^6 \) points.

- Thus, the goal of radiation parameterization is to estimate total radiative flux quickly and accurately, where total is the sum of surface fluxes and vertical RFD.
Flux densities

Upward and downward flux densities need to be determined in order to calculate heating/cooling rates for any layer by

\[
\frac{\partial T}{\partial t} = \frac{1}{\rho c_p} \frac{\partial}{\partial z} \left( F_D - F_U \right)
\]

Historical overview

There are two general radiation parameterization methods:

• The first is an empirical approach that relates bulk properties to the radiative flux, essentially estimating downwelling LW radiation at the ground from surface observations.
Empirical approach

This approach is the simplest, computationally cheapest, and least accurate. The inherent assumptions in this approach neglect RFD above the ground and emission from atmospheric gases except water vapor (Stensrud 2007).

Empirical method

• The earliest radiative transfer models were empirical and were accurate only in the clear sky conditions they were designed for (Goody 1952).

• They were unable to make accurate calculations when scatterers were present since they lacked information regarding the absorption coefficient. Rogers and Walshaw (1966) proposed a LW method known as “cooling to space”.
Two-stream method

The second approach is the two-stream method that solves the LW radiative transfer equations that formulate upward and downward fluxes as a function of height.

$$F_U(z) = \int_0^\infty \pi B_v(0) \tau_v^f(z,0) dv + \int_0^\infty \int_0^\infty \pi B_v(z') \frac{d\tau_v^f}{dz}(z,z') dz' dv$$

$$F_D(z) = \int_0^\infty \pi B_v(z') \frac{d\tau_v^f}{dz'}(z,z') dz' dv$$

Two-stream method

- The first term accounts for attenuation of LW radiation emitted from the surface, while the second term represents the emittance of LW radiation by the atmosphere. accounts for atmospheric contributions (Stensrud 2007; Liou 2002).
- LW parameterization schemes differ as a function of approach to calculate the above integrals (Stensrud 2007).
Two-stream method

• Sasamori (1972) introduced a two-stream method that was later adopted and popularized by Pielke (1984).
• There are several parameterizations that take different approaches to solving the integrals in the full equations (not shown). The first makes a simplifying assumption that eliminates the need to integrate over all viewing angles.

Two-stream method

• The second approach integrates the absorption coefficient over the optical path.
• The third linearly interpolates between stored values for the absorption coefficients that have been calculated over the full range of atmospheric conditions and stored. This approach has higher computational expense than previous (Stresund 2007).
correlated-\(k\) method

- The correlated-\(k\) method provides an alternative to line-by-line integration of RT equations for flux density and transmissivity.
- RT calculations for a given spectral band are performed using a small number of absorption coefficients that are representative of the coefficients for all frequencies in the band.

correlated-\(k\) method

- The correlated-\(k\) method maps \(k(v)\) from spectral space to a space defined by a cumulative probability density function, \(g(k)\), where \(g(k)\) is the fraction of the individual values of \(k(v)\) within the interval \(\Delta v\) with values smaller than \(k\). The mapping transformation, \(v \rightarrow k\) produces a new function, that is monotonic, smooth, and amenable to approximation by summation.
correlated-$k$ method

Transformation of flux transmissivity yields

$$T_v \equiv \frac{1}{\Delta V} \int_{\Delta V} e^{-k_v u} \, dv = \int_0^1 e^{-k(g) u} \, dg$$

Binning the data allows the above equation to be discretized into an approximation

$$T_v = \sum_{j=1}^M e^{-k(g_j) u} \, \Delta g_j$$

that reduces the number of calculations by several orders of magnitude
Absorption coefficients

Absorption coefficients due to CO\textsubscript{2} for a layer \((P = 507\) mb) in the midlatitude summer atmosphere for the spectral range 630–700 cm\textsuperscript{-1} (a) as a function of wavenumber and (b) after being rearranged in ascending order.

\[\text{Absorption Coefficient (cm}^2\text{molecule}^{-1}\text{)}\]

\[\text{Wavenumber (cm}^{-1}\text{)}\]

\[\text{Cumulative Probability } g\]

\[\text{g–space bands & weights} \]

Boundaries and weights of subintervals in \(g\)–space used in RRTM. (From Mlawer et al. 1997)

<table>
<thead>
<tr>
<th>Subinterval</th>
<th>Initial (g) Value</th>
<th>Final (g) Value</th>
<th>Weight</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>0.00000</td>
<td>0.15275</td>
<td>0.15275</td>
</tr>
<tr>
<td>2</td>
<td>0.15275</td>
<td>0.20192</td>
<td>0.14947</td>
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<td>3</td>
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<tr>
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<td>0.57571</td>
<td>0.13169</td>
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<td>0.12149</td>
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<td>0.10193</td>
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<td>0.08328</td>
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<td>0.87911</td>
<td>0.94178</td>
<td>0.06267</td>
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</table>
WRF radiation schemes

- WRF architecture allows use and comparison of various physics algorithms.
- WRF includes two longwave radiation schemes: Rapid Radiative Transfer Model scheme that accounts for multiple bands and trace gases and GFDL scheme that includes cloud microphysics effects.
- Both utilize look-up tables and provide atmospheric heating from radiative flux divergence.

WRF SW radiation schemes

- WRF includes three SW radiation schemes, i.e. Goddard shortwave, GFDL, and simple shortwave schemes, all of which include absorption, reflection, and scattering (Skamarock et al. 2007).
- The primary source of SW radiation is solar insolation that can be scattered, reflected, or absorbed. Reflection causes upward fluxes due to surface albedo.
WRF LW radiation schemes

- LW radiation includes IR radiation absorbed and emitted by gases and the surface. Upward LW radiative flux from the surface is determined by its emissivity, a function of surface temperature and land-use type (Skamarock et al. 2007).
- Positive RFD relates to the radiative warming rate, while negative relates to the radiative cooling rate. Radiative transfer parameterizations can be the most computationally expensive of all the physical parameterizations.

SW radiation

- The factors effecting downward SW flux, include: the albedo and absorption of clouds; solar zenith angle increases path length and reduces; scattering and water vapor absorption in clear air. The combination of these attenuating effects are formulated by:

\[ S_d(z) = \mu S_0 - \int_{z}^{\text{top}} \left( dS_{cs} + dS_{ca} + dS_s + dS_a \right) \]
Simple SW radiation scheme

- The simple SW radiation scheme is based on Dudhia (1989) and is taken from MM5. It has downward integration of solar flux that accounts for clear-air scattering, H$_2$O vapor absorption, and cloud absorption and reflection. It utilizes look-up tables for clouds (Skamarock et al. 2007);
- SW radiation reflected upward by clouds and the surface are ignored. SW radiation calculations are performed every 10 minutes.

RRTM LW Scheme

- The rapid and accurate radiative transfer model (RRTM) aims to calculate fluxes and cooling rates comparable with the line-by-line radiative transfer model (LBLRTM), while performing a smaller number of radiative transfer operations. This is accomplished by use of the correlated-$k$ method, with $k$-distributions obtained from LBLRTM (Mlawer et al. 1997).
RRTM LW Scheme

- LW radiation absorption occurs for H₂O vapor, CO₂, O₃, CH₄, N₂O, CFC-11, CFC-12, CFC-22, and other species. It is necessary to subdivide the LW band into a number of spectral intervals that contain strong absorption due to certain species. Contributions from the major absorbing species are then determined with a high degree of accuracy, while those from the minor species are determined with a less detailed approach (Mlawer et al. 1997). RRTM bands and implemented species are shown in .

Absorption coefficients

Absorption coefficients due to CO₂ for a layer (P = 507 mb) in the midlatitude summer atmosphere for the spectral range 630–700 cm⁻¹ (a) as a function of wavenumber and (b) after being rearranged in ascending order.
RRTM LW Scheme

- Radiative transfer calculations are performed for each subinterval in each band. The subintervals are processed in the same way that a spectral point is processed in the LBLRTM.
- The major difference is the number of required calculations: $10^6$ spectral points per band vs. 16 intervals in g-space per band for LBLRTM and RRTM respectively. RRTM flux and cooling rates are finally compared and validated against those determined from LBLRTM.

### RRTM bands

<table>
<thead>
<tr>
<th>Band Number</th>
<th>Wavenumber Range, cm</th>
<th>Species Implemented in RRTM</th>
<th>Lower* Atmosphere</th>
<th>Middle/Upper+ Atmosphere</th>
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<td>1</td>
<td>10-250</td>
<td>H$_2$O, H$_2$O, CO$_2$, CO$_3$, CO$_3$, CO$_2$, CFC-11, CFC-12, CFC-11, CFC-12</td>
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<td>2</td>
<td>750-1500</td>
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<tr>
<td>3</td>
<td>500-1000</td>
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<td>600-700</td>
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<td>700-820</td>
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<td></td>
</tr>
</tbody>
</table>

*1000-300 mbar except for band 8 (1050-317 mbar).
96-0.01 mbar except for band 4 (317-0.01 mbar).
*Optical depths of these halocarbons are increased to account for other absorption bands of these species that are not implemented.
Gallus and Bresch 2006

- Gallus and Bresch examined rainfall forecast sensitivity as a function of model physics, dynamics, and initial conditions in simulations of 15 rainfall events in the central U.S. during August 2002 (Gallus and Bresch 2006).
- Two dynamical cores and two physics packages were used in a total of four configurations that were all initialized with ETA output. Dynamical cores used were the nonhydrostatic mesoscale model (NMM) and the Advanced Research WRF (ARW).
The first physics package (NCEP) used the Betts-Miller-Janic convection scheme, GFDL radiation package, and Mellor-Yamada-Janic PBL scheme.

The second physics package (NCAR) incorporated the Kain-Fritsch convective scheme, Dudhia rapid radiative transfer model (RRTM), and Yonsei University PBL scheme. Additional physical schemes (e.g. Ferrier et al. microphysics, Noah land surface model) were identical in all runs. Simulations were performed at 8-km grid spacing with 60 vertical layers, using 1200 UTC ETA 40-km Gridded Binary (GRIB) output for initial and lateral boundary conditions (Gallus and Bresch 2006).

Results indicate that NCAR physics with both dynamic cores generally overestimated peak rain rates (Gallus and Bresch 2006) and 3 show a 12–18-h forecast period for WRF runs and observations respectively, indicating greater intensity and finer structure from the NCAR physics.

Each of the simulations has significant differences from the observations. Gallus and Bresch (2006) concluded that peak rain rate sensitivity is more a function of physics package than dynamic core, while total rain volume is more a function of dynamics than physics. The two radiation schemes did not cause notable differences.
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Evaluation of parameterizations

The ability to use different configurations of parameterization schemes is a strong point for WRF. This allows researchers to justapose different combinations and thus better evaluate individual and combined schemes.

Parameterization schemes are constantly evolving, and although the ones identified in this essay represent significant improvements over previous versions, they have the inherent limitations of the era in which they were developed.
Future development

- The new version of the Goddard scheme illustrates this. The new Goddard scheme has a correct two-stream adding approximation in diffuse transmissivity, while the old scheme had an incorrect diffuse transmissivity – a critical bug in the code.

- The new scheme delta-Eddington approximation for reflection and transmittance of direct and diffuse radiation, while the old uses delta-Eddington approximation for direct radiation, but it uses equations in Sagan and Pollock (JGR, 1967) for diffuse radiation.