Tue 4/5/2016

Representation of clouds and precipitation:
- Finish with microphysics

Begin radiation section
- Review of radiation basics
- Representation of radiation in models
- Consideration of WRF radiation schemes

Reminders/announcements:
- MP paper summary assignment – for Thursday
- Upcoming MP experiments: Design your own
Microphysics Section Outline

• Basics of microphysics schemes
  – MP scheme “responsibilities”
  – Distinguishing characteristics: Classes, Distribution, & Processes
  – Why classes matter: Hurricane example
  – Representation of number concentration: Bin vs. Bulk
  – Single, double, and triple moment schemes

• The WRF schemes
  – Calling sequence
  – Defining characteristics: Warm and cold-cloud processes
  – Scheme details: CCN, process representation

• Model simulated radar

• Case-study examples:
  – Winter storm (lake effect)
  – Convective storm
  – Tropical cyclone
Re-Cap from Tuesday

When are high-end MP schemes worth the computational expense?

- Small grid length
- Strong updrafts
- Studying precipitation systems
A few loose ends:

- Confirmed that Xia was correct- no momentum tendencies in the old SAS CP scheme

- Confirmed that Thompson (8) “talks” to RRTMG radiation scheme
Microphysics Options

Recommendations:

• Probably not necessary to use a graupel scheme for $dx > 10$ km
  – Updrafts producing graupel not resolved
  – Cheaper scheme may give similar results

• When resolving individual updrafts, graupel scheme should be used

• Can use different options on different domains

• Think about lofting, physical processes in system being studied
Milbrandt-Yau MP Scheme – Output Variables

- Hydrostatic pressure
- Water vapor mixing ratio
- Cloud water mixing ratio
- Rain water mixing ratio
- Ice mixing ratio
- Snow mixing ratio
- Graupel mixing ratio
- Hail mixing ratio
- Cloud water Number concentration
- Rain Number concentration
- Ice Number concentration
- Snow Number concentration
- Graupel Number concentration
- Hail Number concentration
- Soil temperature
- Soil moisture
- Soil liquid water
- Relative soil moisture
- Previous timestep condensational heating
- Coupled theta tendency due to cumulus scheme
- Coupled \( q_v \) tendency due to cumulus scheme
- Coupled \( q_r \) tendency due to cumulus scheme
- Coupled \( q_c \) tendency due to cumulus scheme
- Coupled \( q_s \) tendency due to cumulus scheme
- Coupled \( q_i \) tendency due to cumulus scheme
- Average vertical velocity for KF cumulus scheme
- Radar reflectivity (\( \lambda = 10 \) cm)
- Cloud fraction
- Coupled x wind tendency due to PBL parameterization
- Coupled y wind tendency due to PBL parameterization
- Coupled theta tendency due to PBL parameterization
- Coupled \( q_v \) tendency due to PBL parameterization
- Coupled \( q_r \) tendency due to PBL parameterization
- Coupled \( q_c \) tendency due to PBL parameterization
- Coupled \( q_i \) tendency due to PBL parameterization
Advantages of double-moment:

- Warm-rain coalescence process represented well
- Sedimentation is better represented
- All source/sink terms are computed as functions of both mass and concentration

**e.g. Accretional growth**

→ increase in mass does not necessarily imply a corresponding increase in number

→ fall velocities are better modelled \([V = V(q, N)]\)
The Milbrandt-Yau Microphysics Scheme:

• Six distinct hydrometeor categories:
  – 2 liquid condensate: cloud and rain
  – 4 solid condensate: ice, snow, graupel and hail

• Size spectrum for each category represented by gamma distribution functions

• Particle categories are characterized by appropriate bulk densities and fallspeed parameters

• Fully double-moment
  – mixing ratio and concentration of each specie is explicitly predicted

• ~50 distinct microphysical processes are parameterized
Milbrandt-Yau Reflectivity
Reference for model simulated radar

11th Conference on Mesoscale Processes

THE USE OF SIMULATED RADAR REFLECTIVITY FIELDS IN THE DIAGNOSIS OF MESOSCALE PHENOMENA FROM HIGH-RESOLUTION WRF MODEL FORECASTS

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“Simulated Radar”

• Often “simulated radar” is not a basic model output, but computed by postprocessor

• Many simulated radar codes include the following assumptions:
  – All particles of a given class have constant density
  – Size distribution fits exponential curve
  – Intercept parameter constant for each class

• In some MP schemes, intercept parameter is \( f(\text{temperature}) \), or double moment, etc.
“Simulated Radar”

• So, what are some “issues” that we should be aware of when using simulated radar?

  – What we get is function of MP scheme used
  
  – Assumptions used in deriving dBZ may not match those in a given MP scheme
  
  – CP precipitation may or may not be represented; NCEP UPP adds a Z-R factor for CP precip

  – No bright bands… we could add that, but why add “error”?

Bottom line: It is always going to be an “apples to oranges” comparison unless MP computes it
Differences in Sim Radar (TN case)
Semester Outline

Model Physics:
1.) Land-Surface Models (LSM)
2.) Turbulence parameterization & the planetary boundary layer (PBL)
3.) Convective parameterization (CP)
4.) Cloud and precipitation microphysics (MP)
5.) Parameterization of radiation

Project:
1.) Topic selection, case identification
2.) Hypothesis development
3.) Control simulation, hypothesis presentation
4.) Experiments and final presentation

Technical:
1.) Running SCM
2.) Running WPS, WRF, postprocessing for real-data cases
3.) Model experiments: Terrain and physics modifications
4.) Analysis and diagnosis of model output
Outline for radiation parameterization section

Radiative transfer

- Review of radiation basics
- Atmospheric radiation
- Model representation strategies
- WRF radiation schemes
- Cloud-radiation interactions: Thompson/RRTMG
Radiation Basics

Radiation is unique among energy transfer mechanisms:
- Can transport energy in absence of a medium
- Interacts with distinct substances in very different ways

Radiative heating differences yield atmospheric circulation, dominant across broad spectrum of temporal/spatial scales

*Radiative flux divergence* is the key driver of local, regional, and global temperature tendencies, circulations

Gaseous absorption/emission relatively easy to handle, but computationally expensive

Cloud/aerosol interactions are more difficult
What is radiation? Why do objects radiate?

Point charge at “A” and associated electric field (lines)

Charge moves from location A to B. This imparts a disturbance in the electric field
Atmospheric Radiation

Assuming familiarity with:

- Blackbody properties: Perfect absorber and emitter at all $\lambda$
- Planck’s law: Irradiance emitted by a blackbody at a given $\lambda$ as $F(T)$
- Wien’s displacement law: Relates $\lambda_{\text{max}}$ to $T$
- Stefan-Boltzmann law: Integrate Planck’s law, blackbody radiation $\propto T^4$
- Kirchoff’s law: A good absorber at a given $\lambda$ is a good emitter at that $\lambda$
- Concept of solid angle (steradian measure)
- Beer’s law: Final intensity equals initial intensity $\times \exp(-\text{optical depth})$

Terminology:
- Two-stream: Only concerned with incoming/outgoing radiation
- Bulk approach: Empirical, based on measurements at surface, very simple treatment, not commonly used any more so won’t discuss
Radiation Review

Why do hotter (blackbody) objects exhibit peak emission at shorter wavelengths than colder objects?

Why do substances exhibit discrete emission/absorption lines?

Why are we concerned with atmospheric CO$_2$ increases when mean concentration $<<$ than 1% of atmosphere?

What physical properties do the radiatively “important” atmospheric gases share, and why?
Radiation Review

Why do hotter (blackbody) objects exhibit peak emission at a shorter wavelength relative to colder objects?

Temperature is a measure of molecular kinetic energy

More kinetic energy, more rapid molecular motions (warmer) means higher frequency oscillations imparted to electric field
Absorptivity of atmospheric gases

- Ozone
- N₂O
- O₂, O₃
- CO₂
- H₂O
- Total

Diagram showing the absorptivity of different gases in the Earth's atmosphere across various wavelengths of radiation.
Why do many substances exhibit discrete absorption lines?

One reason is that discrete absorption/emission lines correspond to electron “normal” and “excited” atomic states.

Also, discrete energies associated with vibrational, rotational oscillations inherent in molecular structures.

Doppler effect, collisions, damping effects broaden lines. Pressure broadening, collision broadening…

One result: “water vapor continuum” – vapor has a broad, background level absorption spectrum, not fully understood - pressure broadening, or due to water dimer?
Why are we so concerned with CO$_2$ increases when the mean concentration is $<<$ than 1% of the atmosphere?

Absorbs in “atmospheric window”, a “greenhouse gas”

What physical properties do “important” atmospheric gases (such as CO$_2$) share, and why?

“Important” gases are usually tri-atomic or more, many more rotational, vibrational absorption/emission modes relative to linear diatomic molecules which comprise the majority of the atmosphere (oxygen, nitrogen, argon)
Radiation Review

**Vibrational** modes for some important atmospheric gases:


Rotational and vibrational modes involve smaller amounts of energy, effective in IR portion of spectrum.
Radiation Review

Rotational modes for some important atmospheric gases:

Linear Diatomic: $N_2$, $O_2$, CO

Linear Triatomic: $CO_2$, $N_2O$

Asymmetric Top (bent triatomic): $H_2O$, $O_3$

Figure 3  Vibrational normal modes of CO$_2$ and H$_2$O molecules. Any pattern of vibration can be projected on to these three modes, which are all orthogonal to one another. Also shown are the wavelengths corresponding to each vibrational mode. See ftp site for color image.
Triatomic molecules interact with radiation in more ways, can absorb/emit lower-energy wavelengths relative to diatomic molecules.

Various molecular motions correspond to radiative absorption and emission.

Rotational and vibrational modes correspond to energy of infrared wavelengths.

Radiation Review

Solar irradiance at TOA (upper curve) & surface (lower curve), as function of wavelength, for:

- 60° zenith angle
- Without aerosol, clouds
- Accounting for vapor, carbon dioxide, ozone and oxygen
Atmospheric Radiation

- Incoming solar: Known quantity
- Top of atmosphere
- Absorption/scattering
- Diffuse solar radiation
- Reflection
- Turbulent energy
- Absorption
- Reflection
- Longwave emission

The effects of processes on solar radiation reaching the Earth's surface are estimated.
Radiative transfer in atmosphere
Radiation in Atmospheric Models

Representation:

- Shortwave absorption, reflection, and scattering in clear-sky conditions
- Longwave absorption and emission in clear-sky conditions
- Case of cloudy or partly cloudy conditions are more complex, for both

Treat long, shortwave portions of spectrum separately: Convenient lack of spectral overlap, different processes

1.) Two-stream approaches: Compute upward, downward radiative flux:
   a.) Narrow-band methods – divide into separate spectral bands
   b.) k-distribution method: use expensive line-by-line models, generate look-up tables for absorption coefficients
      “Rearrange” absorption within spectral band, integrate over absorption coefficient values in band (WRF schemes)
Radiation in Atmospheric Models

CO₂ as f(λ) (a) and "ordered" (b)

Stephens, 1984; Mlawer et al. 1997

RRTM, RRTMG: Use very accurate, expensive line-by-line radiative transfer model to compute absorption coefficients across wide range of atmospheric conditions, create "lookup tables" in scheme
Radiation in Models

Model physics schemes generally operate in “single-column mode” – each grid column treated independently; radiation too.

At what grid length does this become questionable for model shortwave radiation parameterization, and why?

Hit pause, and work through the example in the worksheet provided on the class web page.
Physics, Resolution, & Parameterization  
(modified from Jimy Dudhia, NCAR)

At what grid lengths are parameterizations designed to operate?

\[ \Delta = \text{model grid length} \]

“No Man’s Land” a.k.a. “terra incognita”, “gray zone”…  
Be careful when running models with these grid lengths
Physics, Resolution, & Parameterization
(modified from Jimy Dudhia, NCAR)

At what grid lengths are parameterizations designed to operate?

\[ \Delta = \text{model grid length} \]

Δ = model grid length →

```
<table>
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<th>Physics</th>
<th>Convective Parameterization</th>
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<tbody>
<tr>
<td>&quot;No Man’s Land&quot;</td>
<td></td>
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<table>
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<th>Explicit Convection</th>
<th>Convective Parameterization</th>
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<tr>
<td>3-D Radiation</td>
<td>Two Stream Radiation</td>
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<tr>
<td>LES</td>
<td>PBL Parameterization</td>
</tr>
</tbody>
</table>
```

"No Man’s Land" a.k.a. "terra incognita", "gray zone"…
Be careful when running models with these grid lengths
Radiation in Models

Must predict, diagnose, or prescribe the amount of cloud, absorbing gas, and/or aerosols in each model layer

All absorbers, scatterers, and reflectors in each layer estimated to determine extinction in each layer, ultimately surface shortwave flux

Longwave absorption, emittance by each layer calculated from mean layer temperature, pressure, composition

Absorbed shortwave affects temperature, effects on longwave emission included as well
Radiation in Models

Radiation called less frequently than dynamical time step

Specify `radt` in namelist (default = 30 min, recommend 1 min per km of dx)

NAM radiation scheme called once per simulated hour (!), while dynamics are calculated every 90 seconds

Model sun may be shining after clouds and/or rain have been generated, especially with convection: Fix with `swint_opt`

Problem areas:
  • Geometry of clouds, cloud particles, aerosols
  • The water phase (liquid or ice) of cloud layers
  • Handling of trace gases, radiation interactions
Radiation in Models

Largest errors in short- and longwave radiation calculations result from errors in representation of model clouds.

Large errors can also result from model deficiencies in determining the effects of partial cloudiness.

Issue of model top: How is ozone handled for stratosphere?
Radiation in Models

Comparison of sophisticated radiative transfer models with measurements reveal a discrepancy

Models show excessive amounts of solar radiation reaching the surface relative to observations

What are some processes that lead to extinction of incoming solar radiation that could explain this?
Underestimation of solar global and diffuse radiation measured at Earth’s surface

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Physikalisch-Meteorologisches Observatorium Davos, World Radiation Center, Davos Dorf, Switzerland

Received 29 March 2002; revised 10 July 2002; accepted 10 July 2002; published 29 November 2002.

[1] Climate change perspectives intensified investigations of the radiative balance of the Earth-atmosphere system. At the top of the atmosphere, solar irradiance is known with absolute uncertainty of 0.3% and theoretical models agree with albedo measurements, but solar shortwave radiation observations at Earth’s surface are less than those calculated by radiative-transfer models. This model observation discrepancy (10–25 Wm$^{-2}$) led to a decade-long controversy on unexplained enhanced absorption of shortwave radiation in clear-sky atmospheres as well as in clouds. Here we show evidence for underestimation of surface shortwave irradiance by traditional “unconditioned” global and diffuse pyranometer measurements. Reinvestigations of pyranometer calibration in conjunction with thermal offsets and pyranometer thermal control demonstrate an underestimation of clear-sky solar global, as well as diffuse irradiance by 8–20 Wm$^{-2}$, caused by pyranometer differential cooling. Field measurements with “conditioned” and “unconditioned” pyranometers demonstrate that the so-called night offset is present and considerably larger during daytime measurements, and this not only for diffuse but also for global pyranometer measurements. Long-term comparisons between traditional unconditioned and well-conditioned pyranometer measurements at Davos (midlatitude, 1580 m a.s.l.) show differences of several percent on the annual mean of global irradiance. Even though we are aware that measurements at higher altitudes are subject to larger thermal offsets and not representative for the global average, the results of our experiment lead us to believe that surface solar irradiance, measured in the past throughout the globe by traditional unconditioned pyranometers, is underestimated.

INDEX TERMS: 0325 Atmospheric Composition and Structure: Evolution of the atmosphere; 1610 Global Change: Atmosphere (0315, 0325); 3359 Meteorology and Atmospheric Dynamics: Radiative processes; KEYWORDS: solar radiation, global radiation measurements, enhanced solar absorption, missing absorption, pyranometer calibration, pyranometer thermal offsets
These measurements are currently being analyzed to identify precisely those atmospheric conditions that lead to the radiation biases, to isolate the errors in the radiation and cloud parameterizations that are responsible for the radiation errors, and to evaluate the effects of these radiation errors on the surface energy balance and surface temperature forecasts. For example, one potential source for the observed solar radiation bias errors is the attenuation due to aerosols, because this effect typically is not accounted for in weather forecast models. Aerosol optical depth measurements made during NEHRPT already have been compared with observed and predicted solar radiation from the Eta Model (Zamora et al. 2005). Results indicate that for each 0.1 increase in aerosol optical depth, the observed solar radiation decreases by $-12 \text{ W m}^{-2}$ (Fig. 4). As a result, solar noon radiance errors on days with high aerosol loading can easily reach 60–80 W m$^{-2}$. Applying a simple analytic model, Zamora et al. (2005) found that this magnitude of radiation error can produce a surface skin temperature error on the order of 1 K. Once the error sources for the radiation and cloud parameterizations are identified, improvements to the radiation and cloud parameterizations will then be tested, with the expectation that these will lead to improved forecasts of near-surface conditions.


Results indicated that the BCE mean provided more accurate predictions of 2-m temperature and dewpoint temperature at all forecast times out to 48 h (Fig. 5).

**Fig. 4.** Correlation between aerosol optical depth and the observed (crosses) and Eta Model (triangles) solar irradiances for a zenith angle of 41°, measured on five different cloud-free days.
Model Radiation Processes and Interactions

- Reflection by convective clouds
- Reflection by clouds
- Scattering by aerosols and atmospheric gases
- Absorption, IR emission
- Grid Cell CP scheme active
- Grid Cell Totally overcast
- Grid Cell Partially overcast
- Grid Cell Totally clear

- Infrared
- Solar
- Stratiform cloud
- Clear sky
WRF Radiation Options

• For all schemes currently in WRF:
  – Column schemes (1-dimensional), each column treated independently

  – Fluxes determined as if infinite, horizontally uniform plane

  – Approximation acceptable if vertical thickness of model layers $<<$ horizontal grid length
Radiation in Models

With CP scheme on, where no explicit hydrometeor field produced in convectively precipitating grid cell, does radiation scheme account for convective cloudiness?

Ans: Depends. Convective cloud fraction computed (Slingo 1987), can be used by radiation scheme

For clouds, the **cloud optical depth** is critical parameter:
- Extinction (reduction of parallel beam intensity along path by scattering and absorption)
- Reflective properties
Radiation schemes in models

Tarasova et al. 2006 (Feb Journal of Applied Met. & Climatology)

Eta model shortwave scheme
(Lacis and Hansen 1974, 99)

Accounts for:

• Absorption by H₂O, O₃, CO₂
• Reflection from atmospheric molecules, clouds
• Solar absorption by vapor from Yamamoto (1962) – underestimate of absorption
• Underestimate of absorption due to neglect of O₂, vapor continuum, aerosol forcing
• Result: Too much SW at surface

NASA GSFC shortwave scheme
(Chou and Suarez 1999, 5)

Accounts for:

• Absorption by H₂O, O₃, CO₂, O₂
• Reflection from atmospheric molecules, clouds, aerosols
• Solar absorption by vapor includes H₂O vapor continuum
• Used in NASA models, compares better with observations of SW at surface
Ran workstation Eta model for all of summer month (Jan 2003) when solar forcing maximized

Two sets of model runs:
1.) Original scheme with default Eta SW package
2.) Experimental model with NASA/GSFC SW package

Comparison of SW at surface, other parameters between runs
Mean solar incident radiation at surface, January 2003

Difference: unmodified model - satellite observations: positive bias!

Tarasova et al. (2006)
Implemented NASA GSFC CLIRAD scheme (Chou and Suarez (1999))

*Much better* comparison to other techniques, observations for surface solar

Strong reduction of positive SW bias at surface in most areas

Still 40-60 W/m² positive bias, attributed to cloud interactions

Why might this be *positive* in parts of Brazil?

Difference in incident SW, modified – original surface shortwave, Jan 2003
Tarasova et al. (2006)

Mean convective cloud cover fraction: original scheme

Reduced convective cloud cover in modified model

Fig. 3. (a) Mean convective cloud cover fraction (%) for January 2003 from original model simulation and (b) difference between the modified model and original model simulations of mean cloud cover fraction.
Tarasova et al. (2006)

2-m temperature difference, modified – original

Cooler except where reduced cloudiness
Tarasova et al. (2006)

January 2003 mean daily precipitation (mm): model

January 2003 mean daily precipitation (mm): satellite observations

Unmodified Eta scheme
Tarasova et al. (2006)

Improving radiation scheme resulted in worsened precipitation forecasts!

About right before, too light with modified scheme

Important interactions with other physics schemes

Overestimate of SW at surface:
- Too much heating, destabilization
- Excessive convective precipitation
- Warm bias in near-surface temperatures
WRF Radiation Options
WRF Radiation Options

• These choices impact:
  – Surface air temperature
  – Stability
  – Convective precipitation
  – PBL depth
  – Cloud cover
  – Soil moisture

• But radiation schemes often overlooked as critical source of model error
WRF Radiation Options

IR: clear and cloud upward and downward fluxes, surface emission, interacts strongly with LSM

IR: Cloud-top cooling, and weak clear air cooling

SW: clear and cloudy solar flux, includes annual, diurnal cycles, also upward reflection

SW: Warming effect in clear sky due to absorption, most crucial for surface budget
WRF Radiation Options: Considerations

LW approaches:

Narrow band: Break up spectrum into wavelength bands around absorption/emission lines

Correlated k (absorption) method: orders by line strength, avoids integration over wavelength (RRTM)

Wide band: Use emissivity to re-write radiative flux equations without integration over frequency (just height)

SW approaches:

Here, both absorption and scattering (Rayleigh for short $\lambda$) are important

Must account for both direct and diffuse radiation

Different than LW in that no re-emission, less absorption (water, ozone)
WRF Radiation Options: Considerations

Data needed:

Model provides profiles of T, q, clouds needed for radiation computations

Still need CO$_2$ (well mixed, but seasonal cycle and trend) and ozone (not well mixed at all). Plus other trace gases, and aerosol

Key missing element is measurement of aerosol optical depth, which may partly explain positive bias in model SW relative to observations

Water vapor absorption of SW not consistently handled

Multiple scattering also difficult

SW bias could also relate to measurement error (Dutton, Philipona)

Surface slope effects also important

- Spectral scheme (based on line-by-line (LBL) transfer model) – 16 LW bands
- Look-up tables to draw on accurate LBL calculations (absorption as function of pressure and temperature)
- Interacts with explicit clouds
- Ozone/CO\textsubscript{2} from climatology in WRF-ARW
- Namelist default (what we’ve been running, unless you changed it)
- Accounts for water vapor, CO\textsubscript{2}, O\textsubscript{3}, N\textsubscript{2}O, CH\textsubscript{4}, halocarbons (CFCs)
- Validated for wide range of conditions, seasons, locations
- Designed for versatile applications, including climate and mesoscale models; used in ECHAM5 GCM
- Serious bug fixed in V3.2 (Cavallo) – major cold bias in upper stratosphere
ra lw_physics=1: V3.4 and earlier

**Set molecular weight ratios**

real :: andw, a  ! Molecular weight of dry air / water vapor
ando, a  ! Molecular weight of dry air / ozone
amdc, a  ! Molecular weight of dry air / methane
amdn, ! Molecular weight of dry air / nitrous oxide
amdc1, ! Molecular weight of dry air / CFC11
amdc2 ! Molecular weight of dry air / CFC12

data andw / 1.607758 /
data ando / 0.603461 /
data amdc / 1.805423 /
data amdn / 0.658090 /
data amdc1/ 0.210852 /
data amdc2/ 0.239546 /

**Put in CO2 volume mixing ratio here (330 ppmv)**

! Added H2O volume mixing ratio from standard atmosphere
! above 150 mb (Steven Cavallo, 01/2010).

real :: co2vmr, h2ovmr
data co2vmr / 330.e-6 /
data h2ovmr / 5.00e-6 /

REAL :: ABCW, ABICE, ABRN, ABSN

DATA ABCW /0.144/
DATA ABICE /0.0735/
DATA ABRN /0.339E-3/
DATA ABSN /2.34E-3/

GRAVIT = 6*100.

**MID-LAYER VALUES**

DO K=ktw,kte
RD=P(K)/(R*T(K))*100.
DZ=DELZ(K)
QV(K)=AMAX1(QV(K),1.E-12)
CLDFRC(K)=CLDFRA(K)

**CO₂ = 330 PPMv**
What should be CO₂ value?

Mauna Loa weekly CO₂ reached 400 ppm (399.76 average, May 2013)

Pre-industrial: ~280 ppmv

tp://www.esrl.noaa.gov/gmd/ccgg/trends/
What should be CO$_2$ value?

Mauna Loa weekly CO$_2$ reached 405.6 ppm last week

Pre-industrial: ~280 ppmv

[Graph showing recent daily average Mauna Loa CO$_2$ levels]

http://www.esrl.noaa.gov/gmd/ccgg/trends/
ra_lw_physics=1

= 1, rrtm scheme

(Default for GHG in V3.5: co2vmr=379.e-6, n2ovmr=319.e-9, ch4vmr=1774.e-9; Values used in previous versions: co2vmr=330.e-6, n2ovmr=0., ch4vmr=0.)

= 4, rrtmg scheme

(Default for GHG in V3.5: co2vmr=379.e-6, n2ovmr=319.e-9, ch4vmr=1774.e-9)
Our time is up… this is a good stopping point for today

To re-cap: We began with a brief review of radiation processes and mechanisms

We then considered what models must do in order to represent radiative transfer, including consideration of the validity of 2-stream approach

Next we considered the often-overlooked importance of radiation in model performance and error

Finally, we began a discussion of the WRF radiation schemes

See you Thursday!