Numerical Weather Prediction: Model physics

Steven Cavallo
Recall that we can write a general form of the governing equations as:

\[
\frac{d\phi}{dt} = F_\phi
\]  

(1)

where \( \phi \) is any scalar. In meteorology, \( \phi \) can be \( u, v, w, \theta \), and mass.

Methods used to solve the left-hand side of (1) are usually considered the model “dynamics” while solving the right-hand side of (1) is considered the model “physics.”
Previously, we discussed how the dynamics can be broken into a time tendency and advection term, which can be represented on a grid by finite differencing. Using the Leapfrog method, for the 1-D advection case, we have:

\[
\frac{\phi^{k+1} - \phi^{k-1}}{2\Delta t} = -u \left( \frac{\phi_{i+1}^{k} - \phi_{i-1}^{k}}{2\Delta x} \right) + F_{\phi}^{k}.
\]

The above illustrates that \( \phi \) can be integrated by combining tendencies into one term called \( f(\phi^{k}) \):

\[
\frac{\phi^{k+1} - \phi^{k-1}}{2\Delta t} = f(\phi^{k})
\]

\[
\Rightarrow \phi^{k+1} = \phi^{k-1} + 2\Delta t \ f(\phi^{k}).
\]  

(2)
Model Physics

Let’s apply this to the thermodynamic equation. Letting $\phi = \theta$:

$$\theta^{k+1} = \theta^{k-1} + 2\Delta t \ f(\theta^k).$$  \hspace{1cm} (3)

What is $f(\theta^k)$?
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$$\theta^{k+1} = \theta^{k-1} + 2\Delta t \ f(\theta^k).$$  

(3)

What is $f(\theta^k)$?

$$f(\theta^k) = \text{Advection tendency} + \text{Physics tendencies.}$$  

(4)

What about the $u$ and $v$ momentum equations?
Model Physics

Let’s apply this to the thermodynamic equation. Letting $\phi = \theta$:

$$\theta^{k+1} = \theta^{k-1} + 2\Delta t \ f(\theta^k).$$  \hfill (3)

What is $f(\theta^k)$?

$$f(\theta^k) = \text{Advection tendency + Physics tendencies.}$$  \hfill (4)

What about the $u$ and $v$ momentum equations?

$$f(u^k) = \text{Advection tendency + Pressure gradient tendency + Coriolis tendency + friction tendency.}$$  \hfill (5)
Now let’s step back and focus on the thermodynamic equation. This is the equation where most of the “model physics” is computed. In it’s most general form:

$$\frac{d\theta}{dt} = F_\theta. \quad (6)$$

The right-hand side are the diabatic forcings, or external forcings that can create or destroy $\theta$. Recall that these are the exact forcings that can create or destroy potential vorticity.
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Recall that these are the **exact** forcings that can create or destroy potential vorticity.

The physical forcings that we account for today are those due to radiative processes, phase changes (latent heating), convection, planetary boundary layer (pbl), and explicit mixing:

\[
F_{\theta} = \theta_{t,\text{radiation}} + \theta_{t,\text{latent heating}} + \theta_{t,\text{convection}} + \theta_{t,pbl} + \theta_{t,\text{mixing}}.
\]

(7)
In a numerical model, each of these forcings are predicted *independently* in a separate programming *subroutine* based on our current understanding of how the particular physical processes occur.

In the end, a single tendency is passed back into the main programming module. The final model integration step looks something like this:

\[
\begin{align*}
  f(\theta^k) &= \text{Advection tendency} + F_\theta \\
  &= \theta_{t,\text{advection}} + \theta_{t,\text{radiation}} + \theta_{t,\text{latent heating}} + \theta_{t,\text{convection}} + \theta_{t,\text{pbl}} + \theta_{t,\text{mixing}}
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\]

and so the numerical integration step using a Leapfrog time scheme would look like

\[
\theta^{k+1} = \theta^{k-1} + 2\Delta t \left( f(\theta^k) \right)
= \theta^{k-1} + 2\Delta t \left( \theta_{t,\text{advection}} + \theta_{t,\text{radiation}} + \theta_{t,\text{latent heating}} + \theta_{t,\text{convection}} + \theta_{t,pbl} + \theta_{t,\text{mixing}} \right)
\] (8)
Model Physics

Let’s look at an example: The Advanced Research Weather Research and Forecasting (WRF ARW) model:

- Grid point model; Equations are fully compressible, non-hydrostatic or hydrostatic, with scalar conservation.
- Terrain following hydrostatic pressure vertical coordinate system.
- Developed and maintained at the National Center for Atmospheric Research (NCAR) for research purposes.
- Free to download, free user support.
- User can define any domain, resolution, physics, time step, boundary conditions, initial conditions, etc.
- Time integration uses a Runge-Kutta scheme that is 3rd order accurate:

\[
\begin{align*}
\phi^* &= \phi^k + \frac{\Delta t}{3} f(\phi^k) \\
\phi^{**} &= \phi^k + \frac{\Delta t}{2} f(\phi^*) \\
\phi^{k+1} &= \phi^k + \Delta t f(\phi^{**})
\end{align*}
\]
Model Physics

WRF model computational flowchart:

Begin time step

Runge-Kutta loop (steps 1, 2, and 3)
  (i) advection, p-grad, buoyancy using ($\phi^1$, $\phi^*$, $\phi^{**}$)
  (ii) physics if step 1, save for steps 2 and 3
  (iii) mixing, other non-RK dynamics, save...
  (iv) assemble dynamics tendencies

Acoustic step loop
  (i) advance $U$, $V$, then $\mu$, $Q$, then $w$, $\phi$
  (ii) time-average $U$, $V$, $W$

End acoustic loop
Advancing scalars using time-averaged $U$, $V$, $W$

End Runge-Kutta loop
Adjustment physics (currently microphysics)

End time step
Model Physics

WRF model computational flowchart schematic:

ARW time-step schematic
Model Physics

Shortwave radiation

Earth’s albedo
30% reflected and scattered 31/100

Incoming solar radiation
100 units

Top of atmosphere

20 absorbed by atmosphere and clouds

Direct and diffuse

49 absorbed at surface
Model Physics

Shortwave + longwave radiation
## Model Physics

### Shortwave and longwave radiation

<table>
<thead>
<tr>
<th>Shortwave (SW)</th>
<th>Longwave (LW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Generally warms atmosphere</td>
<td>Generally cools atmosphere</td>
</tr>
<tr>
<td>Depends on latitude, time of year, time of day</td>
<td>Depends on temperature ( (\text{Stefan-Boltzmann} = \sigma T^4) )</td>
</tr>
<tr>
<td>Strongly absorbed by surface, weakly absorbed by atmosphere</td>
<td>Strongly emitted at surface, strong emittance by atmosphere</td>
</tr>
<tr>
<td>Function of albedo</td>
<td>No dependence on albedo</td>
</tr>
<tr>
<td>Strongly absorbed by ozone</td>
<td>Weakly emitted by ozone</td>
</tr>
<tr>
<td>Weakly absorbed by water vapor</td>
<td>Strongly emitted by water vapor</td>
</tr>
<tr>
<td>Depends on carbon dioxide</td>
<td>Depends on carbon dioxide</td>
</tr>
</tbody>
</table>
Model Physics

Surface heat fluxes

No heat transfer

Temperature

Temperature

Temperature
Model Physics

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No heat transfer

<table>
<thead>
<tr>
<th>z</th>
<th>Temperature</th>
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Warms

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Cools

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Temperature
Model Physics

Surface heat fluxes

- No heat transfer
- Upward heat transfer

Temperature

- Warms
- Cools
Model Physics

Surface heat fluxes

No heat transfer

Upward heat transfer

Cools

Warms

Temperature

Temperature

Temperature
Model Physics

Surface heat fluxes
Model Physics

Between atmospheric layers, flow is controlled by the equations of motion. However, the surface is a boundary. That is, **we must parameterize the communication of energy between the atmosphere and surface**. Based on the previous diagram, formulas have been developed to estimate heat, and moisture exchange between the surface and atmosphere:

\[
H_S = \rho c_p C_H U_1 (T_0 - T_1)
\]

\[
H_L = \rho L_v C_H U_1 (q_0 - q_1).
\]

- \(H_S\): Sensible heat flux
- \(H_L\): Latent heat flux
- \(c_p, L_v\): Specific heat of dry air const. \(p\), latent heat of vaporization
- \(C_H, \rho\): Transfer coefficient, air density
- \(U, T, q\): Wind, temperature, mixing ratio
- 0,1 subscripts: 2 meter and 10 meter model levels

Sign convention: Positive (negative) ⇒ upward (downward) flux
Model Physics

How surface physics gets into atmosphere

- Atmospheric Surface Layer
  - Exchange coefficients for heat and moisture
  - Friction stress and water-surface fluxes of heat and moisture

- Land Surface Model
  - Land-surface fluxes of heat and moisture

- PBL
Model Physics

Processes accounted for in Land Surface Models
Model Physics

Processes in Land Surface Models:

- Evapotranspiration, root zone, leaf effects
- Seasonally varying vegetation fraction
- Vegetation categories (e.g. cropland, forest types, etc.), soil categories (e.g. sandy, clay, etc.)
- Fractional snow and ice cover, frozen soil water, melting, runoff
- Sea surface temperature, sea ice, vegetation fraction can be updated during simulation (boundary conditions)
- Urban effects can be included (e.g. buildings, heating and A/C effects, etc.)
Model Physics

Planetary boundary layer (PBL)

Illustration of PBL Processes

- Stable layer/free atmosphere
- Vertical diffusion
- Entrainment
- Nonlocal mixing
- Local mixing
- Surface layer
- Sensible heat flux
- Latent heat flux
- Friction
Planetary boundary layer (PBL)

- Distribute surface fluxes with boundary layer eddy fluxes.
Model Physics

Planetary boundary layer (PBL)

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  - PBL scheme can build up vertical gradients, which may not be sustainable in a model.
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- Schemes assume that PBL eddies are not resolved.
  - Assumptions break down if $\Delta x \ll 1$ km.
  - When $\Delta x \ll 1$ km, model diffusion does the job since the processes are resolved.
Model Physics

Convection

When clouds and moisture occur at scales that are smaller than the model grid spacing allows, then a cumulus parameterization must be used.
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Model Physics

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- 2 categories of convection: Deep and shallow
  - Deep ⇒ over 3-km deep, precipitating
  - Shallow ⇒ less than 3-km deep, non-precipitating
Model Physics

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  - When to trigger a convective column
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- When triggered, scheme will:
  - Activate the grid point as a convective column
  - Compute and pass a heating tendency and a moisture tendency to the right-hand sides of the thermodynamic and water vapor equations.
Model Physics

Model physics: Convection
Model Physics

Convection

- There are 2 classes of cumulus schemes:
  - Adjustment type—Also called a static scheme. Determines what the atmospheric state needs to be after convection and moves toward that state over some time period.
  - Mass-flux type—Also called a dynamic scheme. Evaluates mass flux based on updrafts and downdrafts.
Model Physics

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ALL cumulus schemes have a “trigger” function that determines when to initiate convection at a grid point. Criteria are:

- Presence of CAPE
- Not too much convective inhibition (CIN) (cap strength)
- Minimum cloud depth from parcel ascent
Model Physics

Convection

NSSL WRF; NCAR WRF; HRRR

RAP/RUC; ECMWF

GFS; NARR; CFSR

\( \Delta x \, (\text{km}) \)

1 5 10 15 20 25 30 40

1 Mid-sized supercell resolved at best

No convective parameterization

“Gray area.”

Violations in convective parameterizations

Should use convective parameterization

Absolutely MUST use convective parameterization or else you get ‘grid point storms’
Model Physics

Latent heating (microphysics)

- When model grid spacing is small enough to resolve clouds, then it is handled by a microphysics scheme.
- Water substance in a sample of air may be represented by eight mixing ratios:

\[
\begin{align*}
q_v &: \text{Water vapor} \\
q_c &: \text{Cloud liquid water} \\
q_d &: \text{Drizzle} \\
q_r &: \text{Rainwater} \\
q_l &: \text{Cloud ice} \\
q_s &: \text{Snow} \\
q_g &: \text{Graupel} \\
q_h &: \text{Hail}
\end{align*}
\]
Model Physics

Latent heating (microphysics)
Many microphysics scheme predict based on the bulk continuity model, meaning water substance is conserved.

The most simple model is a warm cloud ($T > 0^\circ\text{C}$), where there is only condensation ($C > 0$) and evaporation ($C < 0$):

$$\frac{dq_v}{dt} = -C$$
$$\frac{dq_c}{dt} = C$$
For a warm, precipitating cloud, the following can occur:

\[ C_c \quad : \quad \text{Condensation of cloud water} \]
\[ E_c \quad : \quad \text{Evaporation of cloud water} \]
\[ E_r \quad : \quad \text{Evaporation of rain water} \]
\[ A_c \quad : \quad \text{Autoconversion}^{1} \quad \text{of cloud water} \]
\[ K_c \quad : \quad \text{Collection of cloud water} \]
\[ F_r \quad : \quad \text{Sedimentation of raindrops} \]

\[ 1 \quad \text{Rate at which cloud water content decreases as particles grow to precipitation size by coalescence and/or vapor diffusion.} \]
Model Physics

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\[ F_r : \text{Sedimentation of raindrops} \]

\(^1\)Rate at which cloud water content decreases as particles grow to precipitation size by coalescence and/or vapor diffusion.

Then the model becomes:

\[
\frac{dq_v}{dt} = -C_c + E_c + E_r
\]

\[
\frac{dq_c}{dt} = +C_c - E_c - A_c - K_c
\]

\[
\frac{dq_r}{dt} = -E_r + A_c + K_c + F_r
\]
Model Physics

Since there were 3 “classes” for which water substance could be classified, the above example would be considered a 3-class microphysics scheme.
Model Physics

When including cold clouds ($T < 0^\circ\text{C}$), an equation for cloud ice and snow must be added, making it a 5-class microphysics scheme.
Of course, you don’t *really* want to know everything that is considered in a microphysics scheme:
Model Physics

Combined, the physics schemes interact, which can be summarized like below:

- Microphysics
- Cumulus
- Radiation
- PBL
- Surface

Connections:
- Microphysics interacts with Cumulus via cloud detrainment.
- Radiation interacts with Surface via non convective rain and convective rain.
- PBL interacts with Surface via surface fluxes SH, LH, and surface T, Qv, wind.
- Surface interacts with Microphysics via downward SW, LW and surface emission/albedo.
Model Physics

When using, running, or creating a new model, ALWAYS keep in mind the scales that a physics parameterization is designed for:

- Simple Microphysics
- Cumulus Parameterization
- Two Stream Radiation/flat surface
- PBL Parameterization

Grey zones:
- Mixed-Phase Microphysics
- 3-D Radiation/slope effects
- LES
Important points and questions for review

- What are 4 different physical processes that are parameterized in a numerical model?

- Suppose you are a forecaster, trying to forecast what the high temperature will be in your forecast area. You have two numerical models to use for forecast guidance. Both models show that it will remain sunny and clear, and that there will be no temperature advection. However, one model shows that a deep layer of higher relative humidities will move over the forecast area while the other does not. How will the forecast high temperatures differ between the 2 models and why?

- Hudson Bay, located in northern Canada, is unfrozen in November but completely freezes over by January. How would a model’s surface heat and moisture fluxes vary between November and January over Hudson Bay?

- What horizontal grid spacing does your model need to have in order to NOT use a cumulus parameterization? Where are convective processes handled in a model when you do not use a cumulus parameterization?

- Name 8 different classes of water substance that may be represented in a microphysical parameterization.