Thu 2/25/2016

Convective parameterization:
  • Mass flux schemes: Fritsch-Chappel and Kain-Fritsch

Reminders/announcements:
- Short “progress report”, due today
- Midterm Thu 3/3 (2014 exam posted on www page)
  • Part of exam will be take-home, summarizing CP papers
  • See BMJ “lab review exercise” on class web page: Practice for exam
- Project hypothesis assignment, due (presented) Tue 3/15
Convective Parameterization

Outline for convective parameterization (CP) section:

A. Concept
   1.) Thought experiment
   2.) Concepts and processes

B. Why CP schemes are needed and matter
   1.) Types of NWP problems affected by CP schemes
   2.) Convective momentum adjustment
   3.) Explicit convection and the “stratus problem”

C. CP Scheme Fundamentals
   1.) Adjustment versus mass-flux schemes
   2.) The Betts-Miller-Janjic CP scheme
   3.) The Fritsch-Chappell and Kain-Fritsch schemes
   4.) Tiedtke and Arakawa-Schubert schemes

D. Modifications to CP schemes, model experiments
• Inclusion of momentum adjustment (or lack thereof) is an important distinction between CP schemes

• Schemes from GCM/global models generally do include momentum adjustment (RUCUTEN, RVCUTEN)

• BMJ scheme representative of an “adjustment” scheme, based on empirical field experiment data from tropics

• BMJ strengths are computational efficiency, simplicity

• BMJ limitations include lack of momentum adjustment, account of downdrafts, and overactive shallow mixing

• Important to recognize that MYJ/BMJ combination works well, by design, with “entrainment” in shallow part of BMJ
BMJ: construction of 1st guess T profile

Cloud top

Return to moist adiabat at cloud top (quadratic interpolation)

REFERENCE TEMP PROFILE

Freezing level

.85 slope of moist adiabat

Moist adiabat passing through LCL for lifted air triggering deep cloud

LCL
First-guess moisture profile

- Cloud top
- Freezing level
- Dew point profile
- Mixing ratio

Δp = -18.75mb
Δp = -58.75mb
Δp = -38.75mb

Dry adiabat

Original LCL
WRF model code - in WRFV3/phys directory

REAL, PARAMETER ::
  DSFC=-3000.
  DTFP=0., EPCF=5.0, EMIN=0.20, EMINT=0.70
  ELW=2.683E6, ENPLO=20000., ENPUP=15000.
  EPSDN=1.05, EPSDT=0.
  EPSNTF=.0001, EPSNTT=.0001, EPSPR=.01E-7
  EPSUP=1.00
  FR=1.00, FSL=0.85, FSS=0.85
  FUP=0.
  PBM=13000., PFRZ=15000., PNO=1000.
  PONE=2500., PQM=20000.
  PSH=20000., PSHU=45000.
  RENP=1./(ENPLO-ENPUP)
  RHLSC=0.00, RHHSC=1.10
  ROW=1.E3
  STABDF=0.90, STABDS=0.90
  STABS=1.0, STRESH=1.10
  DTSHAL=-1.0, TREL=2400.

REAL, PARAMETER ::
  DTTRIGR=-0.0
  DTPTRIGR=DTTRIGR*PONE  ! -- Average parcel virtual T
  DTR=0.001

REAL, PARAMETER ::
  DSFBFL=-3875.*FR
  DSPOFL=-5875.*FR
  DSPTFL=-1875.*FR
  DSFBFS=-3875.
  DSPOFS=-5875.
  DSPTFS=-1875.

REAL, PARAMETER ::
  PL=2500., PLQ=70000., PH=105000.
  THL=210., THH=365., THHQ=325.

INTEGER, PARAMETER ::
  ITB=76, JTB=134, ITBQ=152, JTBQ=440

INTEGER, PARAMETER ::
  ITREFI_MAX=3
Adjusted profiles, optimizing chances of meeting enthalpy constraint
Even with adjustments, could not meet enthalpy constraint. That is, pushing towards the reference profiles would not result in net warming, drying. Result: Shallow.
Shallow convection tendencies:

Temperature

Moisture
Example of BMJ shallow reference profiles

Fig. 9. Model initial condition (thick, light solid lines) and final $T_{ref}$ and $q_{ref}$ from the BMJ shallow convection component (thick, dark solid lines), valid 1200 UTC 1 Jun 2000 at KOKC.
BMJ Shallow Mixing

Why does this matter?

Here’s one example…
Cold-Air Damming (CAD)

One major difficulty is prediction of CAD erosion.

Models tend to erode CAD cold dome too quickly.

CAD characterized by very large static stability... so what can a model *convective* parameterization scheme have to do with CAD erosion?
Coriolis in cold air, which is flowing ageostrophic southward, “banks up” against mountains: Cold and stable at low levels

Bell and Bosart 1988, Mon. Wea. Rev.
Premature CAD Erosion in NAM Forecast

GSO winds: Lighter, left
NAM forecast winds: Bold, right

GSO RAOB (solid)
NAM Model 36-h forecast sounding (dashed)

00Z 31 Oct 2002
Visible Satellite and Surface Observations

What eradicated the stratus in model??

18 UTC 30 Oct 2002
Could BMJ Shallow Mixing Scheme be the Culprit?

Hypothesis 2: Shallow mixing in model CP scheme is responsible

To test, conducted simulations:
1.) Control run, similar to operational NAM

2.) Experiment with shallow portion of BMJ scheme turned off, all else identical
Control vs. No-Shallow: F30
(valid 18 UTC 30 October)

Control (like operational)  No-Shallow

Configuration like operational NAM  No Shallow run (all else identical)
Control vs. No-Shallow: F30
Red/Green is Control
Without shallow mixing scheme, stratus deck holds!

Shallow convection “smoking gun” footprint

~ 200 mb
Shallow component can be overactive in BMJ, can erode even strong inversion layers

“Smoking gun” mixing profiles from shallow scheme evident in forecast soundings when shallow scheme active

This is not to say that the shallow scheme is necessarily bad!
The “Stratus Issue”

- Many current CP schemes include “shallow mixing” (not just BMJ)

- When model run at 4 km grid length, CP scheme typically turned off (cu_physics = 0)

- By turning of CP scheme, user may also remove smaller-scale shallow-mixing component

- This can have unwanted impacts, particular when run in conjunction with local PBL mixing formulations such as MYJ PBL

- Manifestation of this can be excessive saturation at PBL top
## WRF CP scheme summary

<table>
<thead>
<tr>
<th>Cu_physics</th>
<th>Scheme</th>
<th>Uphys feedback</th>
<th>Momentum</th>
<th>Shallow</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>KF</td>
<td>Cloud, rain, ice, snow</td>
<td>No</td>
<td>Yes, with CuP?</td>
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<tr>
<td>2</td>
<td>BMJ</td>
<td>None</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>3</td>
<td>Grell-Freitas</td>
<td>Cloud water, ice</td>
<td>No</td>
<td>Yes (namelist)</td>
</tr>
<tr>
<td>4</td>
<td>Old SAS</td>
<td>Cloud water, ice</td>
<td>No</td>
<td>Yes</td>
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<tr>
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<td>Grell 3-D</td>
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<td>No</td>
<td>Yes (namelist)</td>
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<td>6</td>
<td>Tiedtke</td>
<td>Cloud water, ice</td>
<td>Yes, linear</td>
<td>Yes</td>
</tr>
<tr>
<td>7</td>
<td>Zhang-McF</td>
<td>Cloud water, ice</td>
<td>Yes, better</td>
<td>No</td>
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<td>11</td>
<td>MSKF</td>
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<td>New SAS</td>
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<td>Yes, better</td>
<td>Yes</td>
</tr>
<tr>
<td>16</td>
<td>New Tiedtke</td>
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<td>Yes, better?</td>
<td>Yes</td>
</tr>
<tr>
<td>93</td>
<td>GD-ens</td>
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<td>No</td>
<td>Yes (namelist?)</td>
</tr>
<tr>
<td>99</td>
<td>KF</td>
<td>Cloud, rain, ice, snow</td>
<td>No</td>
<td>No</td>
</tr>
</tbody>
</table>
Downward shortwave, 4-km WRF *Explicit (EC)*
30-h forecast valid 18 UTC 1 April 2005
Downward shortwave, 4-km WRF BMJ CP
30-h forecast valid 18 UTC 1 April 2005
Difference in SWDN, EC-BMJ
WRF4 4-km EC forecast sounding, for stratus grid point
GOES-12 IR Satellite imagery:
Mostly clear across FL at 15, 18 UTC
Clouds with MCS moving into previously clear areas
975-875 mb layer cloud-water mixing ratio: EC
975-875 mb layer cloud-water mixing ratio: BMJ
Preponderance of stratus in EC run resulted in reduced insolation in pre-convective region

Running shallow-only scheme may allow better forecast of pre-convective environment

EC model runs may require shallow mixing (non-precipitating) parameterization package
The Fritsch-Chappell Scheme

Fritsch and Chappel (1980a,b); Zhang and Fritsch (1986); Fritsch and Kain (1993)

Mass-Flux scheme formulation: Uses a 1-D entraining/detraining plume model
Fritsch-Chappell (F-C) Scheme

- Fritsch-Chappell scheme designed for mesoscale convective system simulation (10-30 km grid mesh)
- On 10-30 km grid, can resolve mesoscale convective generation, organization
- 1-D cloud model is used to estimate vertical structure of convective mass flux (implicitly)
- Convective intensity regulated by Available Buoyant Energy (similar to CAPE)
LFC = Level of Free Convection
CIN = Convective Inhibition
LCL = Lifting Condensation Level
Fritsch-Chappell Scheme

\[ \frac{\partial \tilde{\chi}}{\partial t_{\text{conv}}} = \frac{\tilde{\chi} - \chi_0}{\tau_c} \]

where

\( \tilde{\chi} \) is grid-scale variable after convective adjustment
\( \chi_0 \) is variable before adjustment
\( \tau_c \) is characteristic convective time scale

1-D cloud model used to compute vertical structure of convective mass flux (matching constraints)

\( \tau \) (convective time scale) assumed consistent with advective time scale in grid cell (grid length / mean wind)

Require lower limit (30 mins) for small grid lengths
Fritsch-Chappell Scheme

For convective updraft:

\[ \frac{d w}{d t}_{updraft} = g \left( \frac{T_{\text{updraft}} - T_{\text{grid}}}{T_{\text{grid}}} \right) = g \: B \]

Neglect some pressure perturbation effects, water loading
T is virtual temperature
PBE = potential buoyant energy
ABE = available buoyant energy
ABE = PBE only if parcel can reach LFC
Fritsch-Chappell Scheme

\[ A^\hat{BE} = \int_{LFC}^{EL} g \left( \frac{T_{updraft} - T_{grid}}{T_{grid}} \right) dz = 0 \]

^ means after adjustment

Constraint: all ABE removed over convective time scale

Clouds assumed steady state during time needed to transit grid cell (\(\Delta x / \text{mean wind speed}\)), unless > 1 hour

Light winds: time scale capped at 1 hour, lower limit 30 mins
Fritsch-Chappell Scheme

\[
\hat{T} = \frac{1}{A} \left( \hat{T}_{\text{ambient}} A_{\text{ambient}} + \hat{T}_{\text{up}} A_{\text{up}} + \hat{T}_{\text{down}} A_{\text{down}} \right)
\]

Temperature of grid is altered as area-weighted mean of updraft, downdraft, ambient air

Iterative process used to determine areas of up, downdraft needed to remove ABE in time scale

First guess- 1% of grid cell is updraft, downdraft computed from cloud model

If not enough to remove ABE sufficiently fast, iterate with larger updraft area (like having more convective clouds)
F-C Scheme: Trigger Function

Trigger related to grid-scale ascent

\[ T_{\text{updraft}} - T_{LCL} + \Delta T \text{ checked} \]

\[ \Delta T = \text{const} \ w_{\text{grid}_{LCL}}^{1/3} \]

Check lowest 100 mb layer first, lift mixed parcel, find LCL.

If stable, go up 50 mb and evaluate next 100 mb deep layer.

If instability found at any LCL (up to 600-700 mb layer), cloud model determines thermodynamic path of updraft.

Theta-e in updraft computed for LCL, parcel lifted.
Fritsch-Chappell Scheme

\[ \int_{LCL}^{CT} (T_{updraft} - T_{env}) \rho \, dz = 0 \]

- Updraft is mixed through 50-mb increments until above met
- Entrainment along the way, function of cloud depth
- Freezing introduced in updraft at -25°C
- Condensate that is produced above equilibrium level (EL) detrained to environment; moisture to grid scale
- Molinari and Dudek 1992 – classify as “hybrid” CP scheme – offers some interaction with microphysics scheme
Fritsch-Chappell Scheme

- In downdrafts, only evaporative cooling included- no water loading

- Downdraft properties determined analogously to those of updraft, but sub-saturated, and includes melting

- Test cases indicate scheme produces mesoscale convective features: outflow boundaries, meso-highs, etc.

- Stabilization: warming of environment by compensating subsidence, replacement of high sub-cloud $\theta_e$ with lower downdraft values
Fig. 15.2. (a) Mesoscale analysis for 1800 UTC 19 July 1977 (adapted from Hoxit et al. 1978). Heavy dashed lines indicate troughs. Cold- and warm-frontal symbols alternated with double dots indicate moist-downdraft outflow boundaries. The light shading denotes the level 1 radar echoes and the dark shading denotes level 3 (or greater) radar echoes. Reflectivity boundary is not defined if the echo contour is open. A full wind barb is 5 m s⁻¹. (b) Analysis of sea level pressure (mb, solid lines) and surface temperature (°C, dashed lines) for 6-h forecast verifying at 1800 UTC 19 July 1977. Heavy dashed lines indicate troughs. Cold- and warm-frontal symbols alternated with double dots indicate moist-downdraft outflow boundaries. Shading indicates area of active convection at verification time.
The Fritsch-Chappell Scheme

• Johnstown flood case study (Zhang & Fritsch 1986):
  – Not able to reproduce mesoscale features without CP, particularly moist downdrafts

  – Compatibility between CP scheme, grid scale deemed essential:
    • Midlevel warming due to LH release drives lower convergence, upward motion
    • This triggers more convection
The Fritsch-Chappell Scheme

• Problems with FC scheme:
  – Compensating subsidence can be unrealistic
  – Strong environmental winds- convection won’t reside in grid cell long enough, scheme lags convective effects
  – Detrainment takes place at very high altitude- too dry in mid-levels (insufficient detrainment there)
  – No strict conservation properties

• To address these & other deficiencies, Kain-Fritsch (KF) scheme developed
  – K-F uses same fundamental closure assumption as F-C
  – Improved conservation properties for longer runs
Kain-Fritschch Scheme

• Extends FC in several ways:
  – Improved detrainment (includes mid-level moistening)
  – Uses new, more complex and realistic cloud model
  – Formulated to strictly conserve mass, thermal energy, moisture, momentum (FC did not)

• Key assumptions:
  – CAPE-removal is critical closure assumption
  – Conserves mass, thermal energy, momentum
Schematic of Kain-Fritsch scheme, from N. Seaman, COMET Faculty NWP course, 1999.
Kain-Fritsch CP

Recall:

\[
\frac{\partial \bar{\theta}}{\partial t_{cumulus\_convection}} = \frac{L}{\pi} \frac{dq}{dt} - \frac{\partial}{\partial p} \frac{\omega' \theta'}{p}
\]

Kain-Fritsch:

\[
\frac{\partial}{\partial p} \frac{\omega' \theta'}{p} = \frac{\partial}{\partial p} \left[ \omega_u \theta_u + \omega_d \theta_d - (\omega_u + \omega_d) \bar{\theta} \right]
\]

At a given model level (1 denotes bottom, 2 denotes top):

\[
\frac{\Delta \omega' \theta'}{\Delta p} = \frac{1}{\Delta p} \left\{ (\omega_{u2} \theta_{u2} + \omega_{u1} \theta_{u1}) + (\omega_{d2} \theta_{d2} - \omega_{d1} \theta_{d1}) - [(\omega_{u2} + \omega_{d2}) \bar{\theta}_2 - (\omega_{u1} + \omega_{d1}) \bar{\theta}_1] \right\}
\]

Account for entrainment, detrainment, latent effects, e.g.,

\[
\omega_{u2} \theta_{u2} = \omega_{u1} \theta_{u1} - \varepsilon_u \bar{\theta}_m + \delta_u \theta_{um} - \frac{L}{\pi} \omega_{u2} \Delta q_u
\]
Kain-Fritsch Scheme

Mass flux formulation (Kain and Fritsch 1990)

- Entrainment/detrainment rates inversely proportional
- High entrainment (detrainment) rates favored by high (low) parcel buoyancy and moist (dry) environments

Closure:

- Rearranges mass in column until 90% of CAPE removed
- CAPE computed from undilute parcel lifting
- Time scale similar to F-C scheme:

\[ \tau_c = \frac{\Delta x}{V_{LCL\text{-level}5}} \]

- As before, minimum set to 30 minutes; what does this mean at very small grid lengths, < 10 km, with strong winds?
- A key CP assumption is that convection remains within grid cell during adjustment; this ultimately limits grid-length validity of CP
Kain-Fritsch Scheme

...compute convective time scale (timec). The mean wind at the lcl and midtroposphere is used.

\[ \text{wspd}(\text{klcl}) = \sqrt{u_0(\text{klcl}) \cdot u_0(\text{klcl}) + v_0(\text{klcl}) \cdot v_0(\text{klcl})} \]
\[ \text{wspd}(l5) = \sqrt{u_0(l5) \cdot u_0(l5) + v_0(l5) \cdot v_0(l5)} \]
\[ \text{wspd}(\text{ltop}) = \sqrt{u_0(\text{ltop}) \cdot u_0(\text{ltop}) + v_0(\text{ltop}) \cdot v_0(\text{ltop})} \]
\[ \text{vconv} = 0.5 \times (\text{wspd}(\text{klcl}) + \text{wspd}(l5)) \]

...for ela model, dx is a function of location...

\[ \text{timec} = \text{dx}(i,j) / \text{vconv} \]
\[ \text{timec} = \text{dx} / \text{vconv} \]
\[ \text{tadvec} = \text{timec} \]
\[ \text{timec} = \text{amax1}(1800., \text{timec}) \]
\[ \text{timec} = \text{amin1}(3600., \text{timec}) \]
\[ \text{if} (\text{ishall} .eq. 1) \text{timec} = 2400. \]
\[ \text{nic} = \text{nint} (\text{timec} / \text{dt}) \]
\[ \text{timec} = \text{float} (\text{nic}) \times \text{dt} \]

...compute wind shear and precipitation efficiency.

\[ \text{if} (\text{wspd}(\text{ltop}) > \text{wspd}(\text{klcl})) \text{then} \]
\[ \text{shsign} = 1. \]

! 30 minutes >= timec <= 60 minutes
! shallow convection timec = 40 minutes
Kain-Fritsch Scheme

Trigger function: As in Fritsch-Chappell (but options available)

- Lift parcels to LCL, check for buoyance, but “assist” using function related to grid-scale vertical motion:

\[ \delta T_{vv} = k(w_g - c(z))^{1/3} \]

- See kfeta_trigger option in namelist:
  1 = default
  2 = moisture-advection based trigger (Ma and Tan 2009)
  3 = RH-dependent additional perturbation to strengthen default

- Have not experimented with these yet
Kain-Fritsch Scheme

• **Strengths:**
  – Most complete treatment of cloud processes available, feeds cloud and precipitation back to grid scale
  – Downdrafts allow simulation of mesoscale responses
  – Good scheme for land-based, capped convective environment
  – Highly compatible with microphysics schemes- hybrid approach; this scheme is not “greedy”, and shares precip. with microphysics well

• **Weaknesses:**
  – CAPE-based closure not always suited to tropical environments
  – But, seems to do well with tropical cyclones, due to emphasis on grid-scale interaction
KF CP scheme:
- Designed for higher resolution
- Accounts for entrainment/detrainment between cloud, environment
- Feeds cloud material back to grid scale (anvils)
- Unlike BMJ, does generate surface-based cold pool
- Retains more structure in soundings than does BMJ
Enter sounding file name: LBF_980519
Enter forecast hour of sounding: 24
Enter source layer TD change (C): 0.0
Enter the vertical velocity perturbation (CM/S): 0.0

!!! UPWARD MOTION AND CONDITIONAL INSTABILITY FOUND
!!! IN LOWEST 400 mb, SO CHECK FOR CONVECTIVE
!!! INITIATION...

!!! FOR SOURCE LAYER CENTERED AT 870 mb,
!!! CLOUD DEPTH = 310 m - TOO SHALLOW FOR
!!! DEEP CONVECTION !!!

!!! FOR SOURCE LAYER CENTERED AT 847 mb,
!!! CLOUD DEPTH = 280 m - TOO SHALLOW FOR
!!! DEEP CONVECTION !!!

!!! FOR SOURCE LAYER CENTERED AT 831 mb,
!!! CLOUD DEPTH = 7 m - TOO SHALLOW FOR
!!! DEEP CONVECTION !!!

!!! FOR SOURCE LAYER CENTERED AT 812.8678mb,
!!! PARCEL TOO COLD AT LCL !!!

!!! FOR SOURCE LAYER CENTERED AT 793.9261mb,
!!! PARCEL TOO COLD AT LCL !!!
NO KF FROM THIS LAYER - CAP TOO STRONG !!!
NO KF FROM THIS LAYER - UP MOTION TOO WEAK * LCL !!!!
NO KF FROM THIS LAYER - UP MOTION TOO WEAK • LCL !!!
NO KF FROM THIS LAYER - UP MOTION TOO WEAK • LCL !!!
1-D Kain-Fritsch Cumulus Parameterization Scheme

Enter sounding file name: LBF_980519

Enter forecast hour of sounding: 24

Enter source layer TD change (## C): 1.0

Enter the vertical velocity perturbation (## CM/S): 0.00

!!! UPWARD MOTION AND CONDITIONAL INSTABILITY FOUND
!!! IN LOWEST 400 mb, SO CHECK FOR CONVECTIVE
!!! INITIATION...

Pressure at LCL (mb): 827.128 UMB: .5001381
CONVECTIVE RAINFALL: .4591 CM/h
Initial CAPE: 3346.035
Final CAPE: -755.005
Change in CAPE: 122.5642 %
KF 1.9
Repeated

BMJ tendencies for same sounding
Forecast results can be very sensitive to CP scheme!

- Choice of CP scheme can influence location, strength of coastal cyclones (e.g., Mahoney and Lackmann 2006)

- Betts-Miller-Janjic (BMJ) CP scheme tended to produce closed low centers in regions of strong CP activity, while Kain-Fritsch (KF) produced more continuous inverted trough

- Current version of BMJ in WRF-NMM “very active”; recent testing shows strong development of coastal systems
Operational Eta model forecast

MSLP and 6-hourly *convective* precipitation (tenths of inches)

18Z 16 Feb operational run –
Valid at 00Z 18 Feb

BMJ CP
Coastal Front Representation:
2-m T, 10-m streamlines

BMJ
• less-defined coastal front
• farther offshore
• distinct surface cyclone centers

KF
• better-defined coastal front
  • stronger temperature gradient
  • more convergence
• closer to coast
• inverted trough
One *very* recent example of CP import:

- Hurricane Joaquin case
- Two WRF simulations identical, but one uses newer Tiedtke (16), the other uses older Tiedtke (6)
Variations on same scheme can give very different results!

What is different between new and older Tiedtke?
- New trigger functions for both deep and shallow components
- Different convective time scale for deep convection
- New formulation for entrainment/detrainment rates
- Additional ice processes accounted for
- Differences in cloud-scale pressure gradients (for momentum)

Sundqvist (1978), Gregory et al. (1997), Wu and Yanai (1994)