We have reviewed the reasons why NWP models need to parameterize convection, and also the processes and environmental changes that we expect a CP scheme to represent. In class, we will discuss, in general terms, the workings of the Betts-Miller-Janjić (BMJ) and Kain-Fritsch (KF) CP schemes. This worksheet will help you to gain familiarity with the BMJ scheme by presenting a specific example.

A. Adjustment and Mass Flux Schemes

The BMJ scheme is an “adjustment” scheme, meaning that it modifies the model environment by adjusting the lapse rates of both temperature and moisture towards specified “reference profiles” at each grid point, without attempting to simulate the explicit convective process. This adjustment approach is based on the concept of mixing within an unstable layer, and the reference profiles are designed to mimic observed post-convective structures as determined from field experiments (an empirical approach). Convective adjustment schemes are generally best suited for large-scale models and for situations requiring less intensive computational resources. The BMJ epitomizes such schemes, and is a widely used adjustment-style CP scheme.

In contrast to the adjustment scheme approach, the desire for CP appropriate to models with smaller grid lengths helped to motivate the development of “mass flux” schemes. These schemes DO attempt to explicitly formulate and account for convective processes at each grid point. This is accomplished by combining a 1-D cloud model with the assumption that convection acts to restore the grid column to a stratification based on moist parcel stability. The cloud model estimates the properties of the convection and the closure assumption specifies the amount of convection that occurs in order to achieve the desired rate of stabilization. While the mass flux approach is more physically consistent than the empirical adjustment approach, it does have its tradeoffs. Because they are more complex, mass flux schemes introduce new problems that require the schemes to make additional assumptions, and these schemes are therefore more computationally expensive. The accuracy of these schemes can depend on the details of the plume model used, and typically account for entrainment/detrainment, updrafts and downdrafts. The Kain-Fritsch scheme is representative of this class of CP schemes, and the Arakawa-Schubert, Grell, and Tiedtke schemes are examples of other widely used mass-flux type schemes.

B. The Betts-Miller-Janjić (BMJ) Scheme

The operational NAM model, run at the US National Centers for Environmental Prediction/Environmental Modeling Center, uses the BMJ scheme. The original Betts Miller scheme was significantly altered and improved by Janjić (1994) for use in the higher-resolution NAM model (which currently features a 12-km grid length; an inner 4-km nest does not currently use the BMJ scheme). In the BMJ scheme, the temperature and moisture profiles at a given grid point are nudged simultaneously toward a reference profile that has been repeatedly observed in environments modified by convection. This means that once the parameterization scheme is
initiated, the atmosphere is adjusted toward a post-convective environment, with precipitation possibly developing. The deep convection component of the BMJ scheme in the model will adjust to a post-convective profile ONLY if precipitation would result from pushing the model sounding towards the reference profiles (i.e., if activation of deep convection would result in a net warming and drying), otherwise it either does nothing, or initiates its shallow convection component. The BMJ scheme will not trigger convection regardless of the amount of CAPE if the cloud layer is too dry (below a certain threshold). It is less inhibited by a strong capping inversion due to its formulation. In alternate categorizations, the BMJ scheme could be labelled as a “deep control” or “moisture control” scheme, and is “static” in the sense that it is not explicitly representing cloud processes. Note that the BMJ scheme does not adjust momentum.

1. Shallow Convection in the BMJ Scheme

The shallow convective parameterization portion of the BMJ scheme triggers if the cloud depth resulting from the lifting of the most unstable parcel is > 10 hPa deep, < 200 hPa deep, and covers at least two model layers. (Until late 1998, the second threshold value was 290 hPa. Note that there are several versions of the scheme floating around, and the values are tunable, so check the code to confirm settings for the model you are running.) If activated, the shallow scheme in the model determines the modifications to both the temperature and moisture profiles, but does not adjust momentum. The newly modified temperature profile is ultimately adjusted so that the net latent heat release is 0, which means that no precipitation is produced by this process. The modified moisture profile is further changed so that the following constraints will be met:

a.) No precipitation will reach the ground, i.e., the net latent heat release due to the moisture change is zero or the total water vapor in the cloud is unchanged.
b.) The total entropy change due to the shallow convective parameterization must be a small positive quantity. If the entropy change due to a temperature change is negative (the temperature has cooled), then the entropy change due to the moisture change must be positive.

Activation of shallow convection in BMJ means that the moisture will be moved upward, so that net drying will occur near the cloud base and net moistening will occur near the cloud top. It mimics the process of condensation near cloud base (warming and drying) and evaporation near the cloud top (cooling and moistening), so that the net change in the sounding results in no precipitation. The shallow convective scheme is an important component of the NAM model convective forecast due to its role in preparing the pre-convective environment via vertical mixing. It can also impact the maintenance of shallow boundary layer clouds in the model atmosphere. As shown in lecture, and by Baldwin et al. (2002), when this scheme is overactive it can have unintended consequences.

2. Deep Convection in the BMJ Scheme

The BMJ deep convective parameterization scheme is based on the observation that deep convection is a thermodynamically driven process that transports heat and moisture upward to remove or reduce conditional instabilities. This process usually results in the production of precipitation. This portion of the scheme evaluates each grid point and finds the most unstable
parcel in the lowest 130 hPa of the model atmosphere. It calculates cloud depth, and if it is > 200 hPa, the deep convective parameterization continues to other checks.

Once a sufficient cloud depth is detected, the BMJ deep convection scheme then computes the post-convective “reference profiles”, towards which the model atmosphere is adjusted. From the cloud base to the environmental freezing level, the temperature profile is modified to be 85 or 90% of the slope of the moist adiabat that goes through the cloud base. To determine the moisture profile modifications, the scheme uses a procedure that considers both the distance a parcel needs to be lifted to reach saturation, and a measure of the ability of the convective column to transport heat upward, while at the same time producing as little precipitation as possible (known as the "cloud efficiency"). It is then assumed that the convective forcing is proportional to an increasing function of the cloud efficiency. These adjustments are made and additional corrections are then applied to the profiles to conserve enthalpy. This guarantees that if it does rain, that the net latent heat release will be in balance with the net moisture change due to condensation. Precipitation is directly calculated from the amount of latent heat produced by the modification of the soundings. If the resulting precipitation is not positive or if the entropy of the grid point decreases, the deep convection parameterization is aborted, and the shallow convective parameterization is used. Thus, the way to get precipitation from the deep convective scheme is to have the modified moisture profile become drier and the modified temperature profile become warmer. This means that the adjustment created warming and drying such that the net enthalpy is unchanged, but allowed the latent heat of condensation to be released and for precipitation to fall.

Recall that enthalpy is a measure of the internal energy of the system. The change in enthalpy measures the heat imparted to a system during a reversible isobaric process. Generally, the BMJ scheme is quite effective in preventing the development of grid-scale saturation in conditionally unstable environments. This means that it is also very good at suppressing spurious precipitation bulls-eyes at a single or a few grid points. The strength of convection produced by the BMJ scheme is highly moisture-dependent: the more moist the column, the more intense the convection. The convective adjustment parameterization method of BMJ is simple and economical in terms of computer resources. However, since it parameterizes many significant physical processes that can be explicitly represented in higher resolution models, it limits the ability of the NAM to develop realistic mesoscale circulations in convective environments. The BMJ scheme is not linked to the explicit cloud prediction scheme of the model, except through modification of the model relative humidity fields. Owing to these limitations, organized convection in model runs using the BMJ scheme will likely not look realistic in terms of propagation or additional development due to outflow boundaries. In addition to observing the precipitation forecast by the NAM model it is usually possible to determine when and where the BMJ deep convective parameterization scheme has been active because it nudges the environment toward a well-defined (and recognizable) reference profile. NAM model forecast soundings in precipitation areas tend to resemble the profile on the right below.

Next, complete the example exercise that takes us through the process of BMJ convection.
References on Convective Schemes


Exercise: North Platte, NE, Sounding from 19 May 1998

This exercise first takes you through the BMJ scheme, and later we will compare this to the behavior of the KF scheme. This part should take about 20 minutes to complete.

A. Betts-Miller Cumulus Scheme: Unmodified Sounding

A 1-D version of the BM scheme was used to investigate performance with a sounding.

![1-D Betts-Miller Cumulus Parameterization Scheme](image)

Enter sounding file name: LBF_980519
Enter forecast hour of sounding: 24
Enter source layer TD change (C. C): 0.0
Enter cloud layer RH change (C. C): 0.0
Pressure (mb) at Cloud Base: 822.784 At Cloud Top: 201.889

!!! ONLY SHALLOW CONVECTION ALLOWED !!!!!!

Figure 1.1: Output from 1-D version of Betts-Miller-Janjic cumulus scheme for sounding shown.

To answer the following 2 questions, view the sounding and resulting moisture tendencies. Compare the sounding (black lines) to the first guess BMJ adjustment profiles (grey lines).

![Sounding and BMJ Adjustment Profiles](image)

Figure 1.2: Sounding (black) and BMJ first-guess reference profiles (grey or green).
1. How would the sounding temperature profile have to be changed (i.e., warmed or cooled) to resemble the "convectively adjusted" temperature profile? How would the moisture (dew point) profile have to be changed?

The next step within the scheme is to make sure that the net heating of the column is directly proportional to the net drying, i.e.,

$$\sum_{\text{top}}^{\text{btm}} C_p \delta T = - \sum_{\text{top}}^{\text{btm}} L_v \delta q_v$$

2. Do you think that the above enthalpy conservation constraint is satisfied by the BM first-guess profiles? Why or why not?

Figure 1.3: Sounding (black) and BMJ reference profiles (grey or green) with enthalpy constraints (profiles that now satisfy the above constraint on net heating and drying).
3. Now consider the modified reference profiles in Fig. 1.3. Would pushing the sounding towards these modified profiles produce precipitation (i.e., net drying & heating in the column)?

4. Fig. 1.3 says "NEGATIVE PRECIP" at the bottom. What does this mean?

If the BMJ scheme fails to identify reference profiles that produce positive precipitation, it will attempt to generate shallow (non-precipitating) convection. The reference profiles for this adjustment are shown in Figure 1.4.

![Figure 1.4: Shallow convective adjustment](image)

Figure 1.4 contains vertical profiles of temperature and moisture tendencies that will be fed back to the large-scale model domain over time. Note the shallow distribution of heating and moisture tendencies imposed upon the model atmosphere by this adjustment.

![Figure 1.5: Profiles of temperature and moisture tendencies](image)
B. Betts-Miller Cumulus Scheme: Modified Sounding

The BMJ deep convection scheme failed to activate for the previous sounding, because the “enthalpy constraint” failed – pushing the profile towards the reference profiles did not result in a net warming and drying. Therefore, shallow convection resulted. Now, let’s see what happens if we run BMJ again, but with the model cloud layer relative humidity increased by 20%. The purpose of moistening the sounding is to demonstrate the sensitivity of convective initiation in the BMJ scheme to deep layer moisture.

Figure 1.6: Betts-Miller-Janjic cumulus scheme results (with 20% increase in humidity)

Figure 1.7 below displays the original vertical profiles of temperature and moisture (black), the modified dew point profile (grey), and the BMJ first guess reference profiles (parallel grey).
In Figure 1.7, the BMJ profiles have now been adjusted to satisfy the enthalpy constraint for the modified moisture profile.

In Figure 1.8, the BMJ profiles have now been adjusted to satisfy the enthalpy constraint for the modified moisture profile.
5. How would the temperature profile from the sounding have to be changed to resemble the BMJ "convectively adjusted" temperature profile?

6. How much precipitation does the BMJ scheme produce now that the column has been moistened?
Figure 1.9 illustrates the vertical profiles of heating and drying for this sounding as prescribed by the BMJ scheme.

7. Discuss the character of the temperature and moisture changes. Do the changes appear realistic? Note the location of the cooling tendencies relative to the cloud base.

8. Summarize the difference that adding 20% to the relative humidity profile had on the behavior of the BMJ scheme in this example.