An Adaptive Time-Step for Increased Model Efficiency

Todd A. Hutchinson
Weather Services International, Andover, Massachusetts

1. Introduction

The Advanced Research Weather Research and Forecast system (WRF-ARW) uses a 3rd order Runge-Kutta time integration scheme, as described by Skamarock et al. (2005). The time-step length is a user-configurable run-time parameter that remains constant throughout the model run. The user must be cautious in choosing the time-step because a time-step that is too long will cause model instability and simulation failure, while a time-step that is too short will require unnecessary computing power. The minimum necessary time-step length is driven by the most extreme vertical and horizontal motions expected throughout a model simulation. In the WRF-ARW, the recommendation is to set the time-step to 6*dx, where dx is in km and the time-step is in seconds. This recommended time-step provides sufficient model stability for most simulations, however, it often results in unnecessarily long simulations.

This paper presents a method for automatically adapting the Runge-Kutta time-step throughout the model simulation. The time-step is adapted to the maximum value that can support the underlying horizontal and vertical motions. This assures model stability and leads to a shorter total run-time as compared to a static time-step.

2. Implementation

An adaptive time-step has been implemented in WRF-ARW version 2.1.2. Modifications were made to the advective and acoustic components of the Runge-Kutta time-step, as well as to several parameterizations.

a. Advective time-step

The advective model time-step is adjusted to assure that the maximum Courant number in the domain does not exceed the maximum stable Courant number. At the beginning of a model run, the time-step is set to either a user input starting time-step (if namelist variable starting_time_step is set) or 6*dx. After that, at each advective step, the maximum horizontal ($C_h$) and vertical ($C_v$) Courant numbers over the entire three-dimensional grid are calculated. Then the time-step ($dt_n$) is adjusted based on maximum of $C_h$ and $C_v$ ($C_{\text{max}}$) as follows:

If $C_{\text{max}} < C_{\text{target}}$

$$dt_n = \left( \frac{C_{\text{target}}}{C_{\text{max}}} \right) \times dt_{n-1}$$

else

$$dt_n = \left( \frac{C_{\text{target}} - 0.5 \times (C_{\text{max}} - C_{\text{target}})}{C_{\text{max}}} \right) \times dt_{n-1}$$

where $C_{\text{target}}$ is the user input target value for the maximum allowable Courant number, and $dt_{n-1}$ is the time-step at the previous model step. The time-step ($dt_n$) is then limited based on user (or default) inputs (indicated by bold type) as follows:

If $dt_n > \left( \frac{dt_{\text{max}} + 1}{100} \right) \times dt_{n-1}$ then

$$dt_n = dt_{n-1} \times \left( \frac{dt_{\text{max}} + 1}{100} \right)$$

If $dt_n > dt_{\text{max}}$ then

$$dt_n = dt_{\text{max}}$$

If $dt_n < dt_{\text{min}}$ then

$$dt_n = dt_{\text{min}}$$

Finally, if the user has chosen to step to output times by setting the namelist variable step_to_output_time to .true., the time-step will be adjusted based on the time to the next output ($t_{\text{output}}$) so that the model steps exactly to output times as follows:

If $t_{\text{output}} > dt_n$ and $t_{\text{output}} < 2\times dt_n$ then

$$dt_n = 0.5 \times t_{\text{output}}$$

Else if $dt_n \leq t_{\text{output}}$ then

$$dt_n = t_{\text{output}}$$

In order to engage the adaptive time-step, the namelist variable time_step is set to -1. Table 1 below lists additional user-configurable parameters that can be used to adjust the adaptive time-step. The parameters can be included in the domains section of the namelist file. If the parameters are not specified in the namelist file, the indicated default values are used.

| Table 1. User inputs for controlling the adaptive time-step |
|---|---|---|
| Namelist entry | Symbol | Default |
| min_time_step | $dt_{\text{min}}$ | 0 |
| max_time_step | $dt_{\text{max}}$ | 3$\times dt_{\text{start}}$ |
| target_cfl | $C_{\text{target}}$ | 1.1 |
| max_step_increase_pct | $dt_{\text{max inc}}$ | 5 |
| starting_time_step | $dt_{\text{start}}$ | 6$\times dx$ |
| step_to_output_time | .false. |

b. Acoustic time-step

At this time, the acoustic time-step is only
adapted to the grid-spacing of the domain and so that it divides evenly into the advective time-step. It does not directly adapt to the underlying weather conditions as the advective time-step does. Use of the adaptive time-step requires that the acoustic time-step be automatically calculated by setting the namelist variable time_step_sound to 0. WRF will exit with an error if time_step_sound is not 0.

c. **Nesting**

The time-step for nests is calculated in a similar manner as for single-domain simulations. However, in order to assure that the model step for a nest remains coincident with its parents’ model step, the time-step for the nest is decreased to the next value so that it is evenly divisible into its parents’ time-step. Further, the time-step of the nest is only changed when the nest step is coincident with its parents’ model step.

d. **Model output**

An additional output parameter of convective precipitation rate was added. This parameter (named PRATEC) was necessary to account for the varying time-step. Since, for the Kain-Fritsch convective parameterization, convective precipitation is an average over several time-steps, and since the time-step varies, the field of time-step convective precipitation (RAINCV) was no longer useful for calculating precipitation rate. Thus, the new field of PRATEC was added.

### 3. Results

#### a. Test Simulations

In order to assure that the use of the adaptive time-step does not significantly alter the forecast output, a set of twelve simulations was run with both a static and an adaptive time-step. The simulations were chosen to include significant weather events including strong convection and a hurricane (Katrina). The simulations were run for the CONUS domain indicated in Fig. 1. Simulations were run out to 48 hours. The parameterizations that were chosen for these test simulations were Kain-Fritsch convective, Dudhia short-wave radiation, RRTM long-wave radiation, MYJ boundary layer, NOAH LSM and Lin microphysics. Table 2 shows the averages and standard deviations of the differences between the two sets of simulations for surface temperature, accumulated precipitation and 500 hPa winds. As indicated, the 2m temperatures, and 500 hPa winds were virtually unbiased, and the standard deviations were quite low. However, the total precipitation output by the model increased by 4.11%, and the areal coverage of precipitation greater than 1 inch increased by 8.27%. Additional analysis indicated that the increase in precipitation was related to the Lin microphysics scheme. Some preliminary tests with the WSM6 scheme indicated no precipitation bias.

An example of the difference in 48 hour precipitation accumulation for one test simulation is show in Fig. 2. The simulations were initialized with data from 00 UTC 28 August 2005, cover the CONUS domain, and include hurricane Katrina in the Gulf of Mexico. The overall pattern is very similar, however, slight differences can be noted. For example, in the central Gulf of Mexico, the precipitation maxima are larger in the simulation using the adaptive time-step, while in the northern

![Operational domains for which the adaptive time-step has been tested.](image)

Fig. 1. Operational domains for which the adaptive time-step has been tested.
Table 2. Average differences in precipitation, 2-meter temperature and 500 hPa wind, between simulations using static and adaptive time-steps, for 12 test cases. Total and areal coverage of one-inch precipitation (PCP) are for the total accumulated precipitation throughout the run. The 2m temperature (t2m) and 500 hPa u and v components of wind (u500 and v500) are averages over 4 forecast times (12, 24, 36, and 48 hours). Positive values indicate that values for the adaptive time-step simulations were larger than for the static time-step simulations. stdev is the average of the standard deviations from each pair of simulations.

<table>
<thead>
<tr>
<th>Total PCP (%)</th>
<th>PCP stdev (%)</th>
<th>Cvg 1in PCP (%)</th>
<th>t2m (C)</th>
<th>t2m stdev (C)</th>
<th>u500 (m/s)</th>
<th>u500 stdev</th>
<th>v500 (m/s)</th>
<th>v500 stdev</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.11</td>
<td>3.10</td>
<td>8.27</td>
<td>-0.02</td>
<td>0.24</td>
<td>0.58</td>
<td>0.58</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

As indicated in Fig. 3, the total run-time for a simulation varies from run to run. For the CONUS domain, over the 2-month test period, the run-time ranged from 51 to 72 minutes with an average of 60 and a standard deviation of 4.1. Simulations for the same domain using a static time-step typically take about 78 minutes, with a very small standard deviation. Thus, the adaptive time-step has yielded a performance improvement of between 8 and 35%. Further, the run-time variance can be attributed to the variance in the time-step which is a result of the variance in the underlying weather conditions. The NHEM domain run-time ranged from 52 to 63 minutes with an average of 58 and a standard deviation of 2.6. For this domain, the adaptive time-step has yielded a performance improvement of between 32 and 43%, as compared to a static time-step of 120s for the 36 km domain. With tuning, it may be possible to use a longer static time-step, so, the improvement resulting from the adaptive time-step may be less than presented here. We speculate that the smaller variance in run-time for the NHEM simulations is due to the fact that the NHEM domain covers a much larger geographic area than the CONUS domain, and thus, the most extreme of the underlying weather (or vertical and horizontal motions) is likely to vary less from simulation to simulation.

b. Operational Simulations

Several operational domains (see Fig. 1), ranging from 12 km CONUS to 36 km Northern Hemisphere, have been running at WSI with the adaptive time-step since late March 2007. Between 1 April 2007 and part of New York State, the precipitation maxima is larger in the simulation with the static time-step. 31 May 2007, nearly 1500 simulations have been run without failure. Parameterizations that have been exercised in these operational simulations are the same as those utilized in the test simulations described previously. Other parameterizations have not been extensively tested.

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Since it is often necessary to schedule a set amount of compute time for operational simulations,
reducing the run-time for the longest of the simulations would be beneficial. We plan to investigate some of the longer simulations to determine if the adaptive time-step can be more appropriately tuned.

A plot of the time-step values as a function of model step number for a typical CONUS simulation using an adaptive time-step is shown in Fig. 2. For this simulation, the maximum allowable time-step was set to 160s, and the minimum allowable step was set to 60s. Many of the downward spikes in the plot are a result of the ‘step to output’ feature of the adaptive step.

4. Summary

The implementation of the adaptive time-step presented here has shown to provide significant improvements in model efficiency, while maintaining model stability and forecast accuracy. The adaptive time-step was implemented in WRF-ARW version 2.1.2. Porting of the adaptive time-step to WRF-ARW version 2.2 is currently underway.

REFERENCES