An Adaptive Time-Step for Increased Model Efficiency

Todd A. Hutchinson
Weather Services International, Andover, Massachusetts

1. Introduction

Grid-point numerical weather prediction (NWP) models typically integrate forward in time using a constant time-step. Often, the time-step length is a user-configurable run-time parameter that is selected prior to and remains constant throughout a simulation. 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.

An example of such a model is the Advanced Research Weather Research and Forecast system (WRF-ARW) which uses a 3rd order Runge-Kutta time integration scheme, as described by Skamarock et al. (2005). 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. While this provides sufficient model stability for most simulations, it often results in unnecessarily long simulations.

This paper presents a method for automatically adapting WRF-ARW's Runge-Kutta time-step throughout a model simulation. The time-step is dynamically adapted to the maximum that supports 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 3.0. 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 a default of 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_{max}) as follows:

If $C_{max} < \mathbf{C_{target}}$
    $dt_n = (\mathbf{C_{target}} / C_{max}) * dt_{n-1}$
else
    $dt_n = (\mathbf{C_{target}} - 0.5 * (C_{max} - \mathbf{C_{target}})) / C_{max} * dt_{n-1}$

where $\mathbf{C_{target}}$ 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 $dt_n > (\mathbf{dt_{max\_inc}} + 1) / 100 * dt_{n-1}$ then
    $dt_n = dt_{n-1} * (\mathbf{dt_{max\_inc}} + 1) / 100$
If $dt_n > \mathbf{dt_{max}}$ then
    $dt_n = \mathbf{dt_{max}}$
If $dt_n < \mathbf{dt_{min}}$ then
    $dt_n = \mathbf{dt_{min}}$

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_{output}) so that the model steps exactly to output times as follows

If $t_{output} > dt_n$ and $t_{output} < 2*dt_n$ then
    $dt_n = 0.5*t_{output}$.
Else if $dt_n \le t_{output}$ then
    $dt_n = t_{output}$

In order to engage the adaptive time-step, the namelist variable use_adaptive_time_step is set to *.true.*. 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. WRF-ARW user inputs for controlling the adaptive time-step

Namelist entry	Symbol	Default
min_time_step	$\mathbf{dt}_{\mathbf{min}}$	0
max_time_step	$\mathbf{dt}_{\mathbf{max}}$	3*$\mathbf{dt}_{start}$
target_cfl	$\mathbf{C}_{\mathbf{target}}$	1.1
max_step_increase_pct	$\mathbf{dt}_{\mathbf{max\_inc}}$	5
starting_time_step	$\mathbf{dt}_{\mathbf{start}}$	6*$\mathbf{dx}$
step_to_output_time		.false.

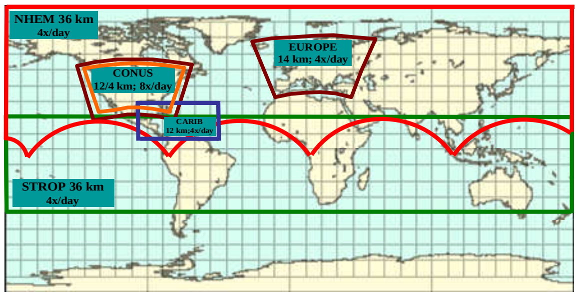

Fig. 1. Domains for which the adaptive time-step has been tested.

b. *Acoustic time-step*

The acoustic time-step is adapted to divide evenly into the advective time-step. 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.

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.

In an experimental version of WRF-ARW that is being developed, the required time-step of the nest is set first, and the outer parent nest is then adjusted to be divisible by the time-step of the inner nest. The time-step of the inner nest is then optimally set and the outer nest is adjusted in order to maintain coincidence with the inner nest. This is advantageous when the inner nest requires more computing resources than the outer nest. In examples in this paper that involve nesting (i.e., operational CONUS simulations described later), this second method of adjusting the inner nest optimally is employed.

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 at 12 km resolution (with a single nest) 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 shown 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 are present. For example, in the central Gulf of Mexico, the precipitation maxima are larger in the simulation using the adaptive time-step.

b. *Operational Simulatoins*

Several operational domains (see Fig. 1), ranging from a North American domain (labeled CONUS) with an outer 12 km and inner 4 km nest to 36 km Northern Hemisphere domain (labeled NHEM), have been running at WSI with the adaptive time-step since late March 2007. During that period, over 17000 simulations were run with only limited failures attributable to use of the adaptive time-step (< 5). When failures did occur, the time-step was tuned to prevent future failures. Parameterizations that were exercised in these operational simulations are the same as those utilized in the test simulations described

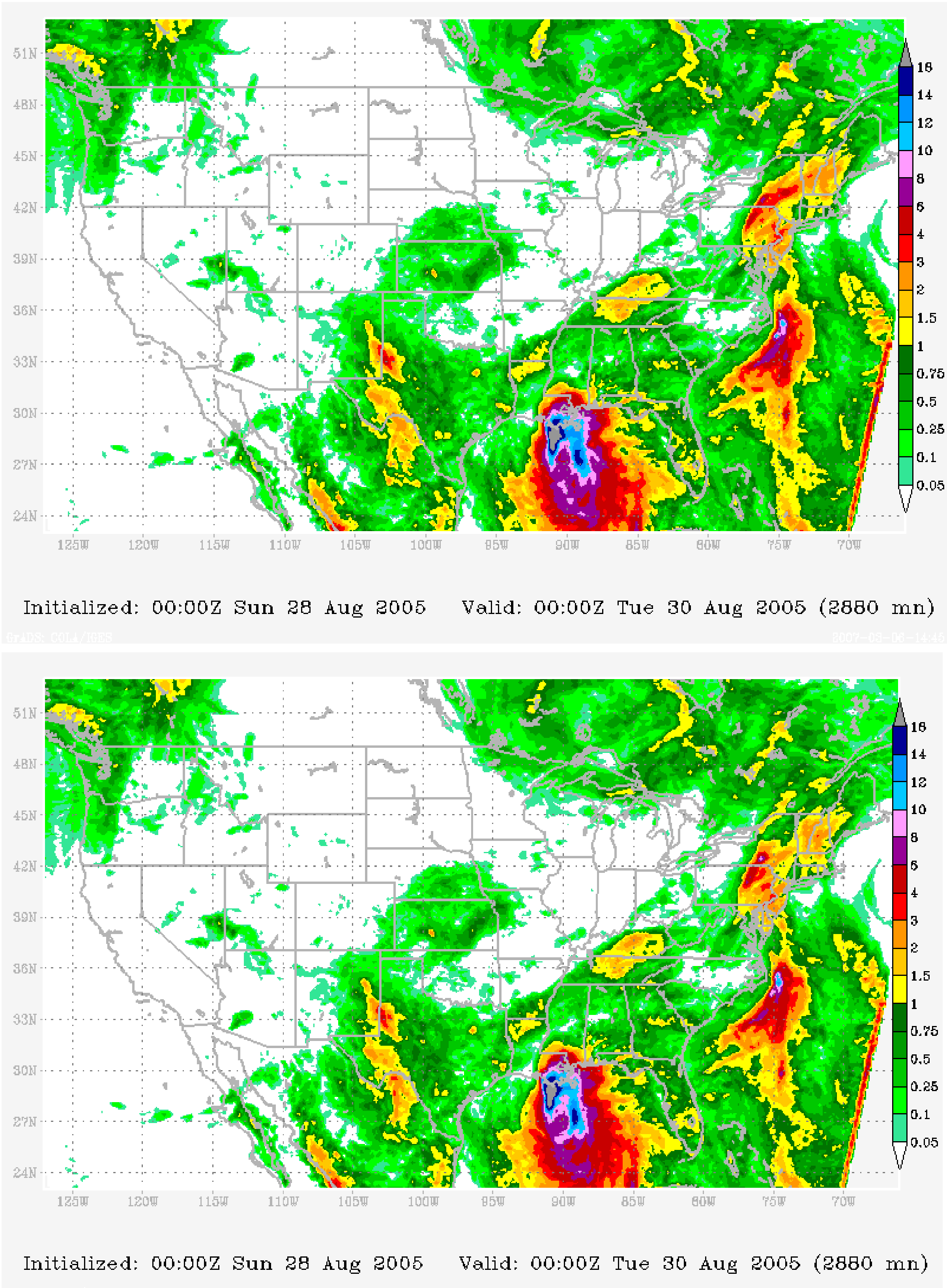

Fig. 2. Comparison of 48 hour accumulated precipitation from WSI's operational 12km CONUS simulati initialized 28 August 2005 for a) static time-step and b) adaptive time-step. Precipitation accumulation is inches as indicated on the scale on the right.

previously. Other parameterizations have not been extensively tested.

As indicated in Fig. 3, the total run-time for a simulation varies from run to run. For the CONUS domain, over the 3-month period between 15 January 2009 and 15 April 2009, the run-time ranged from 64 to 124 minutes with an average of 79 and a standard deviation of 12.5. Simulations for the same domain using a static time-step typically take about 121 minutes, with a very small standard deviation. Thus, the adaptive time-step has yielded a performance improvement of between -2% and 47%. 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 increase in run-time and variability beginning in mid-March appears to be correlated to the onset of the convective season in the United States. While some simulations in April took slightly longer than what was expected with a static time-step (as shown in red), we are uncertain how long those particular simulations would have taken were they run with a static time-step, given that there is variability even with a static time-step.

The NHEM domain test period was from 1 April 2007 through 29 May 2007. During that period, 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. The smaller variance in run-time for the NHEM simulations may be 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.

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. 4. For the 12 km outer domain, the maximum time-step was set to 160 s, and the minimum time-step was set to 60 s. For the inner 4 km domain, the maximum time-step was set to 60 s and the minimum time-step was set to 24 s. The run-time for this simulation was 92 minutes. There is a clear diurnal signal in the time-step length, with the maximum time-step in the 4km domain occurring about 1/3 of the way into the simulation, or at about 03 UTC. The time-step then decreases to a minimum around 2250 steps into the simulation, which is approximately 18 UTC. The general pattern of the 12 km time-step follows closely to that of the 4 km time-step, however, some variations are evident. Many of the shorter steps (downward spikes) are a result of a forced shorter time-step in order to fall exactly upon a data output time. Further, since the time-step of the outer 12 km nest is set to be divisible by the time-step of the 4 km nest, when the 4 km time-step is short, there is often more freedom for the 12 km time-step to extend. This frequently occurs just after data output, when the 4 km time-step has been adjusted. The longer (upward spikes) seen in the 12 km time-step are a result of this freedom..

4. Summary

The implementation of the adaptive time-step presented here has provided significant improvements in model efficiency, while maintaining model stability and forecast accuracy. The adaptive time-step has been included the WRF-ARW model since version 3.0.

REFERENCES

Skamarock, W. C., J. B. Klemp, J. Dudhia, D. O. Gill, D. M. Barker, W. Wang, J. G. Powers, 2007: A description of the Advanced Research WRF Version 2. *NCAR/TN-468+STR*.. NCAR Technical Note. Boulder, CO, USA.

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 simulatio

Total PCP (%)	PCP stdev (%)	Cvg 1in PCP (%)	t2m (C)	t2m stdev (C)	u500 (m/s)	u500 stdev	v500 (m/s)	v500 stdev
4.11	3.10	8.27	-0.02	0.24	0.01	0.58	0.00	0.58

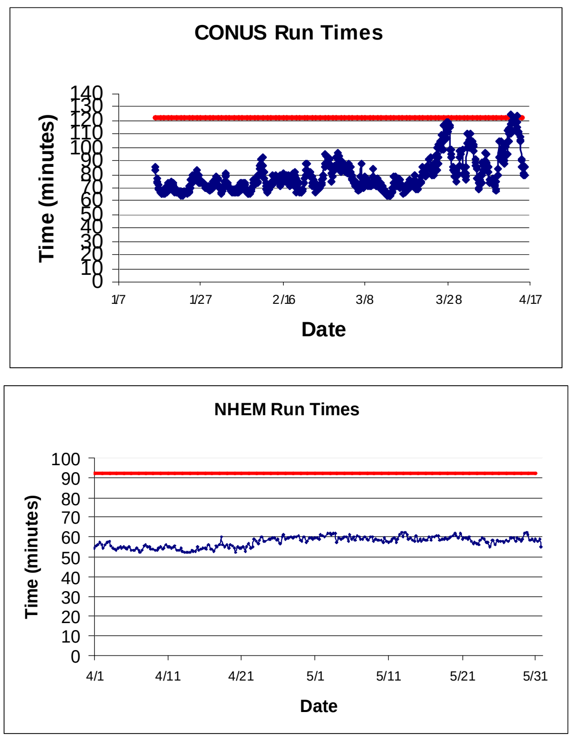

Fig. 3. Run times (blue) for (a) CONUS simulations between 15 January 2009 and 15 April 2009 and (b) NHEM simulations between 1 April 2007 and 29 May 2007 using the adaptive time-step. The typical run-time (red) for a simulation with a static time-step (72s for CONUS, 120s for NHEM) is plotted in red.

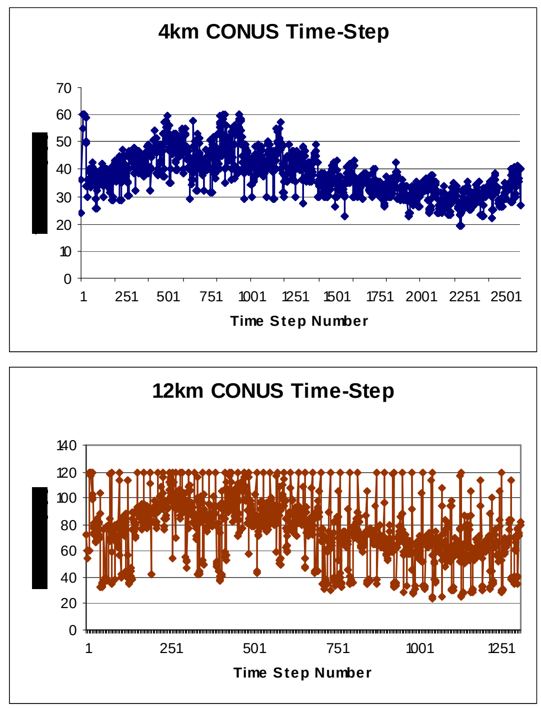

Fig. 4. Model time step as a function of step number for (a) the outer 12km and the (b) inner 4km nest for a CONUS 27 hour simulation beginning 18 UTC 22 May 2009.