Recent Development of NCEP GFS for High Performance Computing

Hann-Ming Henry Juang
Environmental Modeling Center
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Introduction

• NCEP GFS is an NCEP operational global forecast system, mainly refers to a global spectral model.
• GFS comprises model dynamics and physics in hydrostatic system with reduced Gaussian grid, for weather and seasonal forecasts.
• Report on recent developed and developing systems for requiring HPC
High performance computing needs

• Concurrent Ensemble forecast
• Coupled atmospheric-ocean-land
  – High horizontal resolution
• Couple with space environmental model
  – More layers, hybrid coordinates
  – Deep-atmosphere approach
• Adopt ESMF for concurrency & coupling
What is ESMF?

- ESMF provides tools for turning model codes into components with standard interfaces and standard drivers.
- ESMF provides data structures and common utilities that components use for routine services such as data communications, regridding, time management and message logging.

ESMF GOALS
1. Increase scientific productivity by making model components much easier to build, combine, and exchange, and by enabling modelers to take full advantage of high-end computers.
2. Promote new scientific opportunities and services through community building and increased interoperability of codes (impacts in collaboration, code validation and tuning, teaching, migration from research to operations)
G_I --- GFS Initialize
G_R --- GFS Run
G_F --- GFS Finalize
END
### Timing for 11 members

<table>
<thead>
<tr>
<th>T126L64 48 h fcst</th>
<th>#</th>
<th>cpu</th>
<th>Event Wall time(s)</th>
<th>Total Wall time(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concurrent ESMF</td>
<td>11</td>
<td>55</td>
<td>2082</td>
<td>2082</td>
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<tr>
<td>parallel</td>
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<td>5</td>
<td>2086</td>
<td>2086</td>
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<td>sequential</td>
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<td>65</td>
<td>214</td>
<td>2354</td>
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</table>
Concurrent EFS with ESMF

• Concurrently run all ensemble GFS forecast members.
• No extra resource cost with concurrent ESMF as compared to other runs
• The ensemble run members can exchange their information at any time you need.
• One coupler couples all ensemble members and creates the new initial conditions for them to run the next ensemble run.
Improve vertical coordinates

Generalized hybrid
For specific hybrid coordinate

\[ \hat{p}_k = \hat{A}_k + \hat{B}_k p_s + \hat{C}_k \left( \frac{T_{vk-1} + T_{vk}}{T_{0k-1} + T_{0k}} \right)^{C_p / R_d} \]

where variables with ^ are at model interfaces, p, T and ps are function of 3-D space and time A, B, and C are layer constants, only function of k
\[ \hat{p}_k = \hat{A}_k \]

\[ \hat{p}_k = \hat{A}_k + \hat{B}_k p_s \]

\[ \hat{p}_k = \hat{B}_k p_s \]

\[ \hat{p}_k = \hat{C}_k \left( \frac{\hat{T}_{vk}}{\hat{T}_{0k}} \right)^{C_p / R_d} \]

\[ \hat{p}_k = \hat{B}_k p_s + \hat{C}_k \left( \frac{\hat{T}_{vk}}{\hat{T}_{0k}} \right)^{C_p / R_d} \]

\[ \hat{p}_k = \hat{B}_k p_s \]
NH 500 mb Geopotential Height at day 5
for 00Z01JAN2006 – 00Z20JUN2006

Black s: operational GFS    Red t: sigma-theta GFS
SH 500 mb Geopotential Height at day 5
for 00Z01JAN2006 – 00Z20JUN2006

Black s: operational GFS     Red t: sigma-theta GFS
TROPICAL 850 mb Speed at day 3
for 00Z01JAN2006 – 00Z20JUN2006

EXP_s = 2.319
EXP_t = 2.293

Black s: operational GFS    Red t: sigma-theta GFS
TROPICAL 850 mb Vector at day 3
for 00Z01JAN2006 - 00Z20JUN2006

EXPs = 3.447
EXPt = 3.384

Black s: operational GFS   Red t: sigma-theta GFS
TROPICAL 200 mb Speed at day 3
for 00Z01JAN2006 – 00Z20JUN2006

EXP$_{s}$=5.019
EXP$_{t}$=4.877

Black s: operational GFS    Red t: sigma-theta GFS
TROPICAL 200 mb Vector at day 3
for 00Z01JAN2006 – 00Z20JUN2006

EXPs=7.571
EXPt=7.384

Black s: operational GFS    Red t: sigma-theta GFS
Frequency of Superior Performance (%)

- sigma-theta
- parallel M
- operational
- parallel H

2005 hurricane season
Increase vertical layer number

Consider deep atmosphere
Deep Atmosphere

<table>
<thead>
<tr>
<th>Z(km)</th>
<th>T(K)</th>
<th>Cp(J/kg/K)</th>
<th>g(m/s²)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>289</td>
<td>1008.5</td>
<td>9.80</td>
</tr>
<tr>
<td>10</td>
<td>230</td>
<td>1008.5</td>
<td>9.77</td>
</tr>
<tr>
<td>50</td>
<td>261</td>
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<tr>
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<td>9.50</td>
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<tr>
<td>200</td>
<td>950</td>
<td>1134.5</td>
<td>9.20</td>
</tr>
<tr>
<td>300</td>
<td>1059</td>
<td>1220.8</td>
<td>8.92</td>
</tr>
<tr>
<td>400</td>
<td>1068</td>
<td>1265.2</td>
<td>8.70</td>
</tr>
</tbody>
</table>
Consider three dimensional $R$ and $C_P$ by tracers

\[
R = \sum_{i=0}^{N_{\text{tracers}}} R_i q_i = (1 - \sum_{i=1}^{N_{\text{tracers}}} q_i) R_d + \sum_{i=1}^{N_{\text{tracers}}} R_i q_i
\]

\[
C_P = \sum_{i=0}^{N_{\text{tracers}}} C_{P_i} q_i = (1 - \sum_{i=1}^{N_{\text{tracers}}} q_i) C_{P_d} + \sum_{i=1}^{N_{\text{tracers}}} C_{P_i} q_i
\]

We need the values of all $R$ and $C_P$

Our current tracers are specific humidity, ozone and cloud water, thus $N_{\text{tracers}}=3$
From internal energy equation
We have
\[ \rho \frac{dC_p T}{dt} - \frac{dp}{dt} = \rho Q \]
from ideal-gas law, and let \( h = C_p T \) as enthalpy
the above energy equation can be re-written as
\[ \frac{dh}{dt} - \kappa h \frac{dp}{dt} = Q \]
This can be as thermodynamic equation with \( h \) as
prognostic variable, and same form as \( T \).
\[ \frac{dT}{dt} - \kappa T \frac{dp}{dt} = Q_T \]
From horizontal pressure gradient
We have
\[-\frac{1}{\rho} \left( \nabla p \right)_z = -\frac{RT}{p} \left( \nabla p \right)_z = -\frac{\kappa h}{p} \left( \nabla p \right)_z\]

from generalized coordinate transform, above can be written
\[-\frac{\kappa h}{p} \left( \nabla p \right)_z = -\frac{\kappa h}{p} \left[ (\nabla p)_\zeta - \frac{\partial p}{\partial \Phi} (\nabla \Phi)_\zeta \right]\]

from hydrostatic
\[\frac{\partial p}{\partial z} = -\rho g(z)\] and \[\frac{\partial \Phi}{\partial z} = g(z)\] or \[\Phi = \int_o^z g(z) dz\]

the pressure gradient force and hydrostatic can be written as
\[-\frac{\kappa h}{p} \left( \nabla p \right)_z = -\frac{\kappa h}{p} \left( \nabla p \right)_\Phi = -\frac{\kappa h}{p} (\nabla p)_\zeta - (\nabla \Phi)_\zeta\]

\[\frac{\partial \Phi}{\partial \zeta} = -\frac{\kappa h}{p} \frac{\partial p}{\partial \zeta}\]
Put previous into generalized coordinate system

\[
\frac{\partial u^*}{\partial t} = -m^2 u^* \frac{\partial u^*}{a \partial \lambda} - m^2 v^* \frac{\partial v^*}{a \partial \phi} - \zeta \frac{\partial u^*}{a \partial \zeta} - \frac{kh}{p} \frac{\partial p}{a \partial \lambda} \frac{\partial \Phi}{a \partial \lambda} + f_s v^*
\]

\[
\frac{\partial v^*}{\partial t} = -m^2 u^* \frac{\partial v^*}{a \partial \lambda} - m^2 v^* \frac{\partial v^*}{a \partial \phi} - \zeta \frac{\partial v^*}{a \partial \zeta} - \frac{kh}{p} \frac{\partial p}{a \partial \phi} \frac{\partial \Phi}{a \partial \phi} - f_s u^* - m^2 \frac{s^2}{a} \sin \phi
\]

\[
\frac{\partial h}{\partial t} = -m^2 u^* \frac{\partial h}{a \partial \lambda} - m^2 v^* \frac{\partial h}{a \partial \phi} - \zeta \frac{\partial h}{a \partial \zeta} + \frac{kh}{p} \frac{dp}{dt}
\]

\[
\frac{\partial (\partial \Phi / \partial \zeta)}{\partial t} = -m^2 \left( \frac{\partial u^* (\partial \Phi / \partial \zeta)}{a \partial \lambda} + \frac{\partial v^* (\partial \Phi / \partial \zeta)}{a \partial \phi} \right) - \frac{\partial \zeta (\partial \Phi / \partial \zeta)}{\partial \zeta}
\]

\[
\frac{\partial q_i}{\partial t} = -m^2 u^* \frac{\partial q_i}{a \partial \lambda} - m^2 v^* \frac{\partial q_i}{a \partial \phi} - \zeta \frac{\partial q_i}{a \partial \zeta}
\]
Developing Status

• 130 layers with more than 60 layers above is running with coupled space environmental model (SEM) physics
• Enthalpy is implemented into GFS
• Adopt SEM’s physics into GFS
• Change a to be $r=a+z$ in deep atmospheric system with full Coriolis force and vertical momentum equation
Increase horizontal resolution

Test T1278
## Compared to T382

<table>
<thead>
<tr>
<th></th>
<th>T382</th>
<th>T1278</th>
</tr>
</thead>
<tbody>
<tr>
<td># of longitude</td>
<td>1152</td>
<td>3840</td>
</tr>
<tr>
<td># of latitude</td>
<td>576</td>
<td>1920</td>
</tr>
<tr>
<td>Time step (sec)</td>
<td>180</td>
<td>40</td>
</tr>
<tr>
<td># of step/1h</td>
<td>20</td>
<td>90</td>
</tr>
<tr>
<td>Relative # of opr/1h</td>
<td>1</td>
<td>50</td>
</tr>
</tbody>
</table>
Estimation

- T382L64: 1 hour forecast with 31 cpu costs 4 min.
- T1278L64: 1 hour forecast with 375 cpu cost 25 min.
- factor of T1278 (3840*1920*90) to T382 (1152*576*20) is 50.
- 4min*31cpu*50/375=17min, but 25min, it implies a 47% performance reduction.
Developing Status

• Preliminary results show T1278 provides mesoscale features well.
• Very cost, 47% reduction in performance.
• Reduce amount of spectral transform is important, such as reduced spherical transform and/or Lagrangian advection.
• Speedup Legendre transform is another essential act.
• These should be benefit to current resolution of GFS, though T1278 is not in the near future.
Summary

• Recent developments of NCEP GFS
  – Concurrent ensemble
  – Extended vertical resolution
  – Increasing horizontal resolution
    require high performance computing (HPC)
• Further studies to have better modeling
  – Improved spherical transform
  – Less assumption forecast equations
    make NCEP GFS use HPC effectively & efficiently