Testing performance and scaling for NOAA's next generation global modeling system

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17th ECMWF Workshop on  
High Performance Computing in Meteorology

26 October 2016
Next Generation Global Prediction System

- NGGPS is a program within National Weather Service’s 5 year R2O Initiative
- Design, develop, implement in operations a fully coupled atmos/ocean/wave/land/aerosol global prediction system in 2020

http://www.weather.gov/sti/stimodeling_nggps_implementation_atmodynamics
Replacing Global Spectral Model (GSM)

- NGGPS undertaken in parallel with efforts initiated at UKMO and ECMWF
- Hydrostatic GFS at end-of-life
  - Continued GFS operational performance improvements will require non-hydrostatic resolutions
  - Next-Generation computing will require scaling across potentially 100,000’s processors
- Reduce implementation time and risk by evaluating existing non-hydrostatic models and select optimal dynamical core for range of global weather and climate applications in NOAA’s mission
Testing and Implementation Plan

• **Phase 1 (2014-15) – Identify Qualified Dynamic Cores**
  - Evaluate technical performance
    - Performance and Scalability
    - Integration of scheme stability and characteristics

• **Phase 2 (2015-16) – Select Candidate Dynamic Core**
  - Integrate with operational GFS Physics/CCPP
  - Evaluate meteorological performance

• **Phase 3 (2016-2019) – Dynamic Core Integration and Implementation**
  - Implement candidate dynamic core in NEMS
  - Implement Common Community Physics Package
  - Implement data assimilation (4DEnVar with 4D incremental analysis update and stochastic physics)
  - Implement community model environment
Phase 1 testing built on High Impact Weather Prediction Project (HIWPP)

http://hiwpp.noaa.gov/

Table 1. Level 1 Testing Evaluation Criteria

<table>
<thead>
<tr>
<th>Level 1 Eval #</th>
<th>Evaluation Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Bit reproducibility for restart under identical conditions</td>
</tr>
<tr>
<td>2</td>
<td>Solution realism for dry adiabatic flows and simple moist convection</td>
</tr>
<tr>
<td>3</td>
<td>High computational performance (8.5 min/day) and scalability to NWS operational CPU processor counts needed to run 13 km and higher resolutions expected by 2020.</td>
</tr>
<tr>
<td>4</td>
<td>Extensible, well-documented software that is performance portable.</td>
</tr>
<tr>
<td>5</td>
<td>Execution and stability at high horizontal resolution (3 km or less) with realistic physics and orography</td>
</tr>
<tr>
<td>6</td>
<td>Lack of excessive grid imprinting</td>
</tr>
</tbody>
</table>
AVEC formed August 2014 to evaluate and report on performance, scalability and software readiness of NGGPS candidate dycore:

Advanced Computing Evaluation Committee

Chair: John Michalakes, NOAA (IMSG)
Co-chair: Mark Govett, NOAA/ESRL
Rusty Benson, NOAA/GFDL
Tom Black, NOAA/EMC
Henry Juang, NOAA/EMC
Alex Reinecke, NRL
Bill Skamarock, NCAR

Contributors

Michael Duda, NCAR
Thomas Henderson, NOAA/ESRL (CIRA)
Paul Madden, NOAA/ESRL (CIRES)
George Mozdzynski, ECMWF
Ratko Vasic, NOAA/EMC

Phase-1 Benchmarking Report
http://www.weather.gov/media/sti/nggps/AVEC%20Level%201%20Benchmarking%20Report%2008%2020150602.pdf
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<tr>
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<td>NOAA/EMC</td>
<td>Finite difference/Polar Filters</td>
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</tr>
<tr>
<td>GFS-NH *</td>
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* Current operational baseline, non-hydrostatic option under development
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* Current operational baseline, non-hydrostatic option under development, No version of GFS was available for AVEC tests

** Guest dycore, hydrostatic, GFS proxy
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<td>Cubed-Sphere, nested</td>
</tr>
<tr>
<td>NMM-UJ ***</td>
<td>NOAA/EMC</td>
<td>Finite difference</td>
<td>Cubed-Sphere</td>
</tr>
<tr>
<td>GFS-NH *</td>
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** Guest dycore, hydrostatic, GFS proxy

*** NMMB replaced by NMM-UJ
Workloads

- **13 km workload**
  - Represent current and near-term global NWP domains
  - Measure **performance** of the code with respect to operational time-to-solution requirement (8.5 minutes/forecast day)

- **3 km workload**
  - Represent future operational workloads expected within lifetime of NGGPS
  - Measure **scalability**: efficiently utilize many times greater computational resources

- **Baroclinic wave case from HIWPP non-hydrostatic dycore testing (DCMIP 4.1)**
  - Added 10 artificial 3D tracer fields to simulate cost of advection
  - Initialized to checkerboard pattern to trigger cost of monotonic limiters
  - Configurations developed and agreed to by modeling groups and then handed off to AVEC
Computational Resources

• Edison: National Energy Research Scientific Computing Center (DOE/NERSC)
  – 4 million core hours in **two sessions totaling 12 hours** of dedicated machine access
  – 133,824 processor cores in 5,576 dual Intel Xeon **Ivy Bridge** nodes (24 cores per node)
  – Cray Aries network with Dragonfly topology
    – https://www.nersc.gov/users/computational-systems/edison/configuration

• Pre-benchmark development and testing:
  – Stampede: Texas Advanced Computing Center
AVEC Level-1 Evaluations: Performance

AVEC 13km Case: Speed Normalized to Operational Threshold (8.5 mins per day)

 Fraction of Operational Threshold

Number of Edison Cores (CRAY XC-30)

- IFS
- IFS (2016)
- NMM-UJ
- FV3, single precision
- NIM
- MPAS
- NEPTUNE
- 13km Oper. Threshold
AVEC Level-1 Evaluations: Performance

- **Performance:**
  - Number of processor cores needed to meet operational speed requirement with 13-km workload
  - Candidate rankings (fastest to slowest): (1) NMM-UJ, (2) FV3, (3) NIM, (4) MPAS, (5) NEPTUNE

![Graph showing cores required for operational threshold](image-url)

**ECMWF Guest Dycore (hydrostatic)**
**AVEC Level-1 Evaluations: Performance**

- **Performance:**
  - Number of processor cores needed to meet operational speed requirement with 13-km workload
  - Candidate rankings (fastest to slowest): (1) NMM-UJ, (2) FV3, (3) NIM, (4) MPAS, (5) NEPTUNE

![Graph showing cores required for operational threshold](chart.png)

**Legend:**
- Improved MPI Communications
- Switch to single-precision
- Switch from 4\textsuperscript{th} to 3\textsuperscript{rd} degree polynomial

**Systems:**
- IFS
- NMM-UJ
- FV3
- NIM
- MPAS
- NEPTUNE

**Notes:**
- Single precision
- Double precision
AVEC Level-1 Evaluations: Scalability

- Scalability: ability to efficiently use large numbers of processor cores
  - All codes showed good scaling.
  - Candidate rankings (scalability): (1) NEPTUNE, (2) MPAS, (3) NIM, (4) FV3, (5) NMM-UJ

(Higher is Better)
Phase-1 Report and Recommendation

- **NIM** produced reasonable mountain wave and supercell solutions.
  - Excessive noise near grid scale in B-wave solution.
  - Full physics forecasts excessively damped.
- **NEPTUNE** was not able to produce full physics 3-km forecasts.
  - B-wave too smooth, 4-km supercell not split by 90 mins.
- **NMM-UJ** did not produce realistic solutions for the mountain wave and supercell tests.
  - Vertical velocity fields from full physics forecasts did not show signatures expected from resolved convection.

- **FV3, MPAS** produced highest quality solutions overall.
  - More similar to each other than other models for all tests.
  - Some concern about MPAS’s computational cost
  - **Recommended that FV3 and MPAS proceed to Phase-2 Testing**

Phase-1 Benchmarking Report
http://www.weather.gov/media/sti/nggps/AVEC%20Level%20Benchmarking%20Report%202008%2020150602.pdf
NGGPS Phase 2 Testing

- Dycore Test Group – Jeff Whitaker, test mgr. (NOAA/ESRL)
  - V. Ramswamy (NOAA/GFDL), K. Kelleher (NOAA/ESRL), M. Peng (NRL), H. Tolman (NOAA/NWS)
  - Consultants: R. Gall (U. Miami), R. Rood (U. Michigan), J. Thuburn (U. Exeter)

- Phase 2 AVEC committee
  - Rusty Benson (GFDL), Michael Duda (NCAR), Mark Govett (NOAA/ESRL), Mike Young (NOAA/NCEP), and JM

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<thead>
<tr>
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</tr>
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<tbody>
<tr>
<td>1</td>
<td>Plan for relaxing shallow atmosphere approximation (deep atmosphere dynamics)*</td>
</tr>
<tr>
<td>2</td>
<td>Accurate conservation of mass, tracers, entropy, and energy</td>
</tr>
<tr>
<td>3</td>
<td>Robust model solutions under a wide range of realistic atmospheric initial conditions using a common (GFS) physics package</td>
</tr>
<tr>
<td>4</td>
<td>Computational performance with GFS physics</td>
</tr>
<tr>
<td>5</td>
<td>Demonstration of variable resolution and/or nesting capabilities, including supercell tests and physically realistic simulations of convection in the high-resolution region</td>
</tr>
<tr>
<td>6</td>
<td>Stable, conservative long integrations with realistic climate statistics</td>
</tr>
<tr>
<td>7</td>
<td>Code adaptable to NEMS/ESMF*</td>
</tr>
<tr>
<td>8</td>
<td>Detailed dycore documentation, including documentation of vertical grid, numerical filters, time-integration scheme and variable resolution and/or nesting capabilities*</td>
</tr>
<tr>
<td>9</td>
<td>Evaluation of performance in cycled data assimilation</td>
</tr>
<tr>
<td>10</td>
<td>Implementation Plan (including costs)*</td>
</tr>
</tbody>
</table>
Methodology

- Performance testing with GFS physics (Crit. #4)
  - GFS physics runs with double (64b) fp precision
  - Configurations must be same as tested for Crit. #3
  - 3 nominal resolutions: 15km, 13km, 11km; 63 levels
  - Dedicated access to Cori Phase-1 system at NERSC (52K core Haswell) [https://www.nersc.gov](https://www.nersc.gov)
  - Multiple runs varying numbers of processors to straddle 8.5 min/day simulation rate

Thanks to NERSC director Dr. Sudip Dosanjh and NERSC staff members Rebecca Hartman-Baker, Clayton Bagwell, Richard Gerber, Nick Wright, Woo-Sun Yang, and Helen He. Rebecca Hartman-Baker, Clayton Bagwell, Richard Gerber, Nick Wright, Woo-Sun Yang, Helen Ye
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**Eval. Criterion #4 -- Performance with GFS Physics**

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<thead>
<tr>
<th></th>
<th>FV-3</th>
<th>MPAS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nominal resolution (km)</td>
<td>13.03 (equat.), 12.05 (avg.)</td>
<td>13</td>
</tr>
<tr>
<td>Grid Points</td>
<td>3,538,944</td>
<td>3,504,642</td>
</tr>
<tr>
<td>Vertical Layers</td>
<td>63</td>
<td>63</td>
</tr>
<tr>
<td>Time Step (sim. sec)</td>
<td>112.5 (dyn.), 18.75 (acous.)</td>
<td>75 (transport), 37.5 (dynamics), 18.75 (acoustic)</td>
</tr>
<tr>
<td>Radiation Time Step</td>
<td>3600</td>
<td>3600</td>
</tr>
<tr>
<td>Physics (other) Time Step</td>
<td>225</td>
<td>225</td>
</tr>
<tr>
<td>Tracers</td>
<td>3</td>
<td>3</td>
</tr>
</tbody>
</table>

Coarser than nominal resolution (km)

|                      | 15.64 (equat.), 14.46 (avg.) | 15                                  |
| Grid Points           | 2,547,600                     | 2,621,442                          |
| Vertical Layers       | 63                             | 63                                 |
| Time Step             | 225 (dyn.), 22.5 (acous.)     | 90 (transport), 45 (dynamics), 22.5 (acoustic) |
| Radiation Time Step   | 3600                           | 3600                               |
| Physics Time Step     | 225                            | 180                                |

Finer than nominal resolution (km)

|                      | 11.72 (equat.), 10.34 (avg.) | 11                                  |
| Grid Points           | 4,816,896                     | 4,858,092                          |
| Vertical Layers       | 63                             | 63                                 |
| Time Step             | 112.5 (dyn.), 16.07 (acous.)  | 60 (transport), 30 (dynamics), 15 (acoustic) |
| Radiation Time Step   | 3600                           | 3600                               |
| Physics Time Step     | 225                            | 180                                |
Methodology

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<table>
<thead>
<tr>
<th>dx</th>
<th>FV3 gt</th>
<th>FV3 lt</th>
<th>MPAS gt</th>
<th>MPAS mid</th>
<th>MPAS lt</th>
<th>MPAS dt=112.5 gt</th>
<th>MPAS dt=112.5 mid</th>
<th>MPAS dt=112.5 lt</th>
</tr>
</thead>
<tbody>
<tr>
<td>coarser</td>
<td>15.64/14.46</td>
<td>768</td>
<td>960</td>
<td>1920</td>
<td>2304</td>
<td>2816</td>
<td></td>
<td></td>
</tr>
<tr>
<td>nominal</td>
<td>13.03/12.05</td>
<td>1152</td>
<td>1536</td>
<td>2752</td>
<td>4160</td>
<td>4800</td>
<td></td>
<td></td>
</tr>
<tr>
<td>finer</td>
<td>11.72/10.34</td>
<td>1536</td>
<td>2352</td>
<td>4608</td>
<td>5760</td>
<td>6912</td>
<td></td>
<td></td>
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Rebecca Hartman-Baker, Clayton Bagwell, Richard Gerber, Nick Wright, Woo-Sun Yang, and Helen Ye
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- time-per-time step in microseconds
- time-per-time step minus physics (i.e., cost of dycore)
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<thead>
<tr>
<th>time stamp</th>
<th>case name</th>
<th>all (sec)</th>
<th>dyn (sec)</th>
<th>#cores</th>
<th>clipped=0.5\cdot\text{stdv}</th>
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<tbody>
<tr>
<td>20160428075535</td>
<td>13km lt dt reduced</td>
<td>9.32018</td>
<td>7.28292</td>
<td>4160</td>
<td>clipped=0.5\cdot\text{stdv}</td>
</tr>
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- time-per-time step in microseconds
- time-per-time step minus physics (i.e., cost of dycore)
Figure 2: Cores required to meeting 8.5 minutes per day forecast speed requirement for operations at 15, 13, and 11 km horizontal resolution. All cases used 63 vertical levels. Colored bars show time with GFS physics; insets show the fraction of cores required by the dycore alone. The estimated number of cores required to run the 13 km operational GFS in 8.5 minutes on NCEP’s WCOSS Cray XC40 is shown for comparison.
Efficiency of tracer transport

- How efficient is advection with additional 3D tracers
- Run benchmarks with additional tracers on the number of cores with performance closest to 8.5 min/day on Cori
- FV3 cost increased 1.5x with additional 30 tracers
- MPAS cost increased 2.5x with 30 tracers

<table>
<thead>
<tr>
<th></th>
<th>Cores</th>
<th>Number of tracers / Minutes</th>
<th>Factor (lowest to highest)</th>
</tr>
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<tbody>
<tr>
<td>MPAS</td>
<td>4800</td>
<td>3 / 8</td>
<td>2.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>18 / 14.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>33 / 19.8</td>
<td></td>
</tr>
<tr>
<td>FV3</td>
<td>1536</td>
<td>3 / 8.14</td>
<td>1.5 (1.53 adjusted)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 / 9.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30 / 12.0</td>
<td></td>
</tr>
</tbody>
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*correction applied, above
Nesting/Mesh refinement efficiency

Definition of nesting efficiency $E$:

$$a_{\alpha} = \text{area of domain (5.101e14 m}^2)$$

$$a_h = \text{area of refinement (FV3: 2.52e13 m}^2; \text{MPAS: 2.82e13 m}^2)$$

$$r = \frac{a_h}{a_{\alpha}} \quad \leftarrow \text{fraction of domain at high resolution (for uniform resolution domain, } r = 1)$$

$$dx_L \quad \leftarrow \text{lowest resolution in non-uniform resolution run}$$

$$dx_H \quad \leftarrow \text{highest resolution in non-uniform resolution run}$$

$$C = r \left(\frac{dx_L}{dx_H}\right)^3 + (1 - r) \quad \leftarrow \text{idealized cost for a run, assuming constant cost per cell step}$$

$$S_{\text{ideal}} = \left(\frac{dx_L}{dx_H}\right)^3 \quad \leftarrow C_{\text{uniform}}$$

$$S_{\text{ideal}} = r \left(\frac{dx_L}{dx_H}\right)^3 + 1 - r \quad \leftarrow C_{\text{refined}}$$

$$S_{\text{measured}} \quad \leftarrow \text{measured time for uniform 3 km resolution run}$$

$$S_{\text{measured}} \quad \leftarrow \text{measured time for non-uniform resolution run}$$

$$E = \frac{S_{\text{measured}}}{S_{\text{ideal}}}$$

Figure 4: Definition of nesting efficiency and calculation using measured speed of non-uniform domain (nested or mesh-refined) domain and speed for a globally-uniform 3 km domain. The FV3 uniform and non-uniform resolution runs used 3072 processor cores. The MPAS uniform and non-uniform runs used 8192 processor cores.
### Nesting/Mesh refinement efficiency

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<tr>
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<tr>
<td>Ag (global domain area m(^2))</td>
<td>5.101E+14</td>
<td>5.101E+14</td>
</tr>
<tr>
<td>Ah (high res area m(^2))</td>
<td>2.52E+13</td>
<td>2.82E+13</td>
</tr>
<tr>
<td>(r = \frac{ah}{ag})</td>
<td>0.0494</td>
<td>0.0553</td>
</tr>
<tr>
<td>(dx_{low})</td>
<td>14</td>
<td>15</td>
</tr>
<tr>
<td>(dx_{high})</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>(\frac{dx_{l}}{dx_{h}})</td>
<td>4.67</td>
<td>5.00</td>
</tr>
<tr>
<td>((\frac{dx_{l}}{dx_{h}})^3)</td>
<td>101.63</td>
<td>125.00</td>
</tr>
<tr>
<td>(C_{uniform}) (ideal)</td>
<td>101.63</td>
<td>125.00</td>
</tr>
<tr>
<td>(C_{refined}) (ideal)</td>
<td>5.97</td>
<td>7.86</td>
</tr>
<tr>
<td>(S_{ideal, speedup from refinement})</td>
<td>17.02</td>
<td>15.91</td>
</tr>
<tr>
<td>(T_{uniform}) (measured)</td>
<td>345.93</td>
<td>344.65</td>
</tr>
<tr>
<td>(T_{refined}) (measured)</td>
<td>20.98</td>
<td>34.10</td>
</tr>
<tr>
<td>(S_{measured, speedup from refinement})</td>
<td>16.49</td>
<td>10.11</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>96.9%</td>
<td>63.5%</td>
</tr>
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Figure 4: Definition of nesting efficiency and calculation using measured speed of non-uniform domain (nested or mesh-refined) domain and speed for a globally-uniform 3 km domain. The FV3 uniform and non-uniform resolution runs used 3072 processor cores. The MPAS uniform and non-uniform runs used 8192 processor cores.
Dycore Test Group Recommends FV3

• “FV3 performed much better than MPAS in real-world tests with operational GFS physics and performed at significantly less computational cost. MPAS did not exhibit any clear-cut offsetting advantages in other aspects of the test suite. Therefore, DTG recommends that the National Weather Service adopt the FV3 atmospheric dynamical core in the Next Generation Global Prediction System.”

Actions

• NWS Director approves the DTG recommendation on 26 July 2016

http://www.weather.gov/sti/stimodeling_nggps_implementation_atmdynamics
Phase 3

• Global model dynamical core selected (GFDL FV3) and Phase 3 integration is underway
  – Unified model strategic planning is underway
• Teams continue to identify, prioritize and develop model component and system improvements for NGGPS. Related plans include:
  – Accelerated evolution of model physics
    – Developing/implementing Common Community Physics Package (CCPP)
  – Data assimilation improvements
  – Enhanced across-team coordination
  – Accelerated model component and system development and integration of community development
• Community Involvement
  – Coordinating proposal-driven scientific development by universities, federal labs, and testbeds
  – Employment of GMTB
  – Collaboration with JCSDA through JEDI
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  – Data assimilation improvements
  – Accelerated model component and system development and integration of community development into testing at EMC
• Community Involvement
  – Coordinating proposal driven scientific development by universities, federal labs, and testbeds (including 2016 FFO selections);
  – Employment of GMTB;
  – Collaboration with JCSDA for next gen data assimilation system
Acknowledgements

NGGPS Dycore Test Group Members:
Chair: Dr. Ming Ji, Director, NOAA NWS Office of Science and Technology Integration
External Consultants:
- Dr. Robert Gall, University of Miami
- Dr. Richard Rood, University of Michigan
- Dr. John Thuburn, University of Exeter
Candidate Dycore Representatives:
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- Dr. Venkatachalam Ramaswamy, Director, NOAA Geophysical Fluid Dynamics Laboratory (GFDL)
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- Dr. Chris Davis*, Director, Mesoscale and Microscale Meteorology Laboratory, National Center for Atmospheric Research (NCAR)
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- Dr. Stan Benjamin (NOAA, ESRL)
- Dr. James Doyle (Navy, NRL)
Technical Observer: Dr. Rohit Mathur, (Environmental Protection Agency [EPA])
NGGPS Staff:
- Steve Warren
- Sherrie Morris

STI Modeling Program Website:
http://www.weather.gov/sti/stimodeling

Information NGGPS:
http://www.weather.gov/sti/stimodeling_nggps

Information on NGGPS dycore testing is available at:
http://www.weather.gov/sti/stimodeling_nggps_implementation_atmdynamics

Information on Grants:
http://www.weather.gov/sti/stigrants
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**Figure 3.2:** 10-day forecast 200 hPa kinetic energy (KE) spectra, averaged over all 74 forecasts. Reference power-law spectra corresponding to powers of -3 and -5/3 are shown for reference, as well as scales corresponding to 4 and 10 times the nominal grid resolution.
NGGPS Phase 2 Test Plan

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Figure 3.5: 500 hPa 5-day forecast anomaly correlation time series for the Northern Hemisphere poleward of 20 degrees.
Idealized tests

• **Baroclinic wave test with embedded fronts** (DCMIP 4.1).
  – Dynamics strongly forces solution to shortest resolvable scales.
  – Shows impact of truncation error near quasi-singular points on computational grid ("grid imprinting").
  – 15/30/60/120 km horizontal resolutions with 30 and 60 vertical levels.

• **Non-hydrostatic mtn waves on a reduced-radius sphere** (like DCMIP 2.1/2.2).
  – Shows ability to simulate non-hydrostatic gravity waves excited by flow over orography.
  – 3 tests: M1 (uniform flow over a ridge-like mountain), M2 (uniform flow over circular mountain), M3 (vertically sheared flow over a circular mountain). Solutions are all quasi-linear.

• **Idealized supercell thunderstorm on a reduced-radius sphere.**
  – Convection is initiated with a warm bubble in a convectively unstable sounding in vertical shear.
  – Simple Kessler warm-rain microphysics, free-slip lower boundary (no boundary layer).
  – Splitting supercell storms result after 1-2 hours of integration.
  – 0.5/1/2/4 km horizontal resolutions.
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* NCAR ceased participation and withdrew from DTG on 20 May 2016

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- Dr. James Doyle (Navy, NRL)

Technical Observer: Dr. Rohit Mathur, {Environmental Protection Agency (EPA)}

NGGPS Staff:
- Steve Warren
- Sherrie Morris
Baroclinic Wave (sfc wind speed at day 9, 15-km resolution)
Supercell (2500-m w at 90 mins, 4-km)
72-h 3-km forecast test

• ‘Stress-test’ dycores by running with full-physics, high-resolution orography, ICs from operational NWP system.
  – Different physics suites used in each model.

• Two cases chosen:
  – Hurricane Sandy 2012102418 (also includes WPAC typhoon).
  – Great Plains tornado outbreak (3-day period beginning 2013051800). Includes Moore OK EF5 tornado around 00UTC May 19.

• Focus not on forecast skill, but on ability of dycores to run stably and produce reasonable detail in tropical cyclones and severe convection.
  – Also look at global quantities like KE spectra, total integrated precipitation/water vapor/dry mass.
Moore Tornado (w at 500 hPa)
**NGGPS Phase 2 Test Plan**

- **Dycore Test Group** – Jeff Whitaker, test mgr. (NOAA/ESRL)
  - V. Ramswamy (NOAA/GFDL), K. Kelleher (NOAA/ESRL), M. Peng (NRL), H. Tolman (NOAA/NWS)
  - Consultants: R. Gall (U. Miami), R. Rood (U. Michigan), J. Thuburn (U. Exeter)

- **Phase 2 AVEC committee**
  - Rusty Benson (GFDL), Michael Duda (NCAR), Mark Govett (NOAA/ESRL), Mike Young (NOAA/NCEP), and JM

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