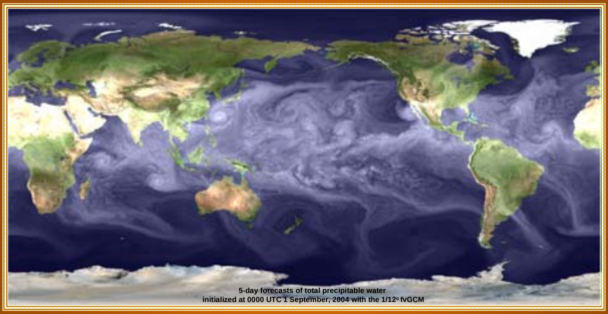
High-impact Tropical Weather Prediction with the NASA Multi-scale Modeling System



Bo-Wen Shen
NASA/GSFC and UMCP/ESSIC

Collaborators (since 2004)

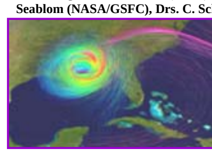
NASA/GSFC: Wei-Kuo Tao (lead), Jiun-Dar Chern, Oreste Reale, Christa Peters-Lidard, Kuo-Sen Kuo (GSFC), Tsengdar Lee (HQ)

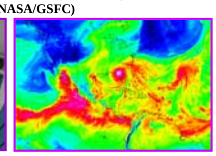
NASA/JPL: Jui-lin (Frank) Li, Peggy Li

NOAA: Robert Atlas (AOML), Shian-Jiann Lin (GFDL)

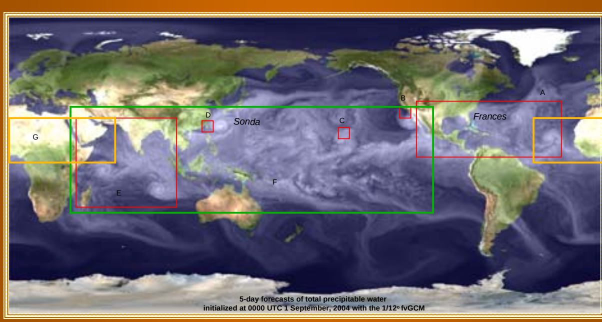
NASA/ARC: Bryan Green, Chris Henze, Piyush Mehrotra, Johnny Chang, Robert Ciotti

Acknowledgements: Dr. K.-M. Lau (GSFC), Dr. A. Busalacchi (UMCP/ESSIC), Dr. R. Anthes (NCAR), Dr. E. Kalnay (UMCP), Prof. R. Pielke (CSU), Dr. W. Washington (NCAR), Prof. C.-C. Wu (NTU), Drs. C.-P. Cheng, J.-S. Hong, and S.-Y. Chou (CWB) and Dr. H.-C. Yeh, Drs. D. Anderson and J. Entin (NASA/HQ), Mr. M. Seablom (NASA/GSFC), Drs. C. Schulbach (NASA/ARC) and P. Webster (NASA/GSFC)





Global Mesoscale Modeling on the NASA Columbia Supercomputer



F: Madden-Julian Oscillation (MJO)
G: African Easterly Wave (AEW)
D: Asian Mei-Yu Front
E: Twin Tropical Cyclones
A: Atlantic Hurricanes
B: Catalina Eddy
C: Hawaiian Lee Wakes

Selected References

(all work were done on the NASA Columbia supercomputer)

- **Shen, B.-W.,** W.-K. Tao, Jiundar Chern, and R. Atlas, 2008: Scalability Improvements in the NASA Goddard Multiscale Modeling Framework for Tropical Cyclone Climate Studies. High Performance Computing in Asia-Pacific Region, 2009. Proceedings. Tenth International Conference on Volume, issue. March 2-5, 2009. *(submitted).*
- **Shen, B.-W. and W.-K. Tao**, 2008: Predicting the Formation of Tropical Cyclone Nargis (2008) with a High-resolution Global Model. SC2008 International Conference for High Performance Computing, Networking, Storage and Analysis. Austin, Texas, November 15-21, 2008. (poster)
- **Tao, W.-K**., D. Anderson, R. Atlas, J. Chern, P. Houser, A. Hou, S. Lang, W. Lau, C. Peters-Lidard, R. Kakar, S. Kumar, W. Lapenta, X. Li, T. Matsui, R. Rienecker, **B.-W. Shen**, J. J. Shi, J. Simpson, and X. Zeng, 2008: A Goddard Multi-Scale Modeling System with Unified Physics. World Climate Research Programme Global Energy and Water Cycle Experiment (WCRP/GEWEX) Newsletter, Vol 18, No 1, 6-8.
- **Shen, B.-W., W.-K. Tao**, R. Atlas, Y.-L. Lin, O. Reale, J.-D. Chern, C. D. Peters-Lidard, K.-S. Kuo , **2007:** Forecasts of Tropical Cyclogenesis with a Global Mesoscale Model: Preliminary Results with Six Tropical Cyclones.Under revision.
- **Shen, B.-W., W.-K. Tao**, et al, **2007:** Multiscale Simulations of a Mei-Yu Front accompanied by a Drifting Meso-cyclone with a Global Mesoscale Model. presented at the CMMAP meeting. In preparation for publication.
- Biswas, R., M. J. Aftosmis, C. Kiris, and **B.-W. Shen**, 2007: Petascale Computing: Impact on Future NASA Missions. Petascale Computing: Architectures and Algorithms (D. Bader, ed.), Chapman and Hall / CRC Press, to appear in November, 2007
- **Shen, B.-W., W.-K. Tao**, R. Atlas, T. Lee, O. Reale, J.-D. Chern, S.-J. Lin, J. Chang, C. Henze, **J.-L. Li**, **2006c:** Hurricane Forecasts with a Global Mesoscale-resolving Model on the NASA Columbia Supercomputer, AGU 2006 Fall Meeting, December 11-16, 2006. (Sixty-four track and intensity forecasts of intense hurricanes in 2004 and 2005 are presented.)
- **Shen, B.-W.,** R. Atlas, O. Oreale, S.-J Lin, J.-D. Chern, J. Chang, C. Henze, and **J.-L. Li**, **2006b**: Hurricane Forecasts with a Global Mesoscale-Resolving Model: Preliminary Results with Hurricane Katrina (2005) Geophys. Res. Lett., L13813, doi:10.1029/2006GL026143. *(highlighted in Science magazine and selected as a Journal Highlight by the American Geophysical Union)*
- **Shen, B.-W.,** R. Atlas, J.-D. Chern, O. Reale, S.-J. Lin, T. Lee, and J. Change **2006a:** The 0.125 degree Finite Volume General Mesoscale Circulation Model: Preliminary simulations of mesoscale vortices. Geophys. Res. Lett., 33, L05801, doi:10.1029/2005GL024594.
- Atlas, R., O. Reale, **B.-W. Shen**, S.-J. Lin, J.-D. Chern, W. Putman, T. Lee, K.-S. Yeh, M. Bosilovich, and J. Radakovich, **2005:** Hurricane forecasting with the high-resolution NASA finite-volume General Circulation Model, Geophysical Research Letters, 32, L03801, doi:10.1029/2004GL021513. *(selected as a Journal Highlight by the American Geophysical Union)*

Presentations/Reprints/Reports

1. Shen, B.-W., W.-K. Tao, R. Atlas, 2008. Predicting Tropical Cyclogenesis with a Global Mesoscale Model: Preliminary Results with Very Severe Cyclonic Storm Nargis (2008). AGU 2008 Fall Meeting, San Francisco, December 15-19, 2008.
2. Shen, B.-W. 2008: Tropical Cyclogenesis Simulated with a Global Mesoscale Model on NASA Supercomputers: Very Severe Tropical Cyclonic Storm Nargis (2008). National Taiwan University, Taipei, Taiwan, October 16, 2008. (an invited talk)
3. Shen, B.-W. 2008: Global Mesoscale Modeling, Concurrent Visualizations, and Supercomputing Systems: Application to High-impact Tropical Weather Predictions. National Central University, Chung-Li, Taiwan, October 14, 2008. (an invited talk)
4. Shen, B.-W. 2008: Global Mesoscale Modeling on the NASA Columbia Supercomputer: Application to Hurricane Forecasts. Central Weather Bureau, Taipei, Taiwan, October 13, 2008. (an invited talk).
5. Shen, B.-W. : Predicting Tropical Cyclogenesis with a Global Mesoscale Model: Preliminary Results with Very Severe Cyclonic Storm Nargis Mesoscale Modeling, Concurrent Visualizations, and Supercomputing Systems: Application to Hurricane Forecasts. National Taiwan Normal University, Taipei, October 7, 2008. (an invited talk)
6. Shen, B.-W. and W.-K. Tao, 2008: Tropical Cyclogenesis Revealed in Global Mesoscale Simulations: Very Severe Cyclonic System Nargis (2008). CMMAP Team Meeting, Fort Collins, Colorado, July 29-31, 2008.
7. Shen, B.-W. 2008: Global Chern, C. D. Peters-Lidard, and J.-L. Li, 2008: Extended-Range Predictions of Madden-Julian Oscillations with the Goddard Multi-scale Modeling System. CMMAP Team Meeting, Fort Collins, Colorado, July 29-31, 2008.
8. Shen, B.-W., W.-K. Tao, J.-D. Chern, et al., 2008: A study on the Comparisons of Goddard MMF Simulations with SP-CAM and Satellite Data. CMMAP Team Meeting, Fort Collins, Colorado, July 29-31, 2008.
9. Shen, B.-W. W.-K. Tao, Roger Shi et al., 2008: Using a Multiscale Modeling Approach to Simulate and Forecast hurricanes. Hurricane Forecast Improvement Project (HFIP) Workshop, Miami, March 11-12, 2008.
10. Shen, B.-W., W.-K. Tao, R. Atlas, 2007: Hurricane Mdoeling and Supercomputing: Can a global mesoscale model be useful in improving forecasts of tropical cyclogenesis? AGU 2007 Fall Meeting, San Francisco, December 10-14, 2007.
11. Shen, B.-W., W.-K. Tao et al., 2007: Global Mesoscale Modeling on the NASA Columbia Supercomputer: Application to Weather and Hurricane Forecasts. International Workshop on Computational Hydrometeorology and Prof. H. L. Kuo's Memorial Symposium. National Center of High-performance Computing, Hsin-chu, Taiwan, October 15-17, 2007. (an invited talk)
12. Shen, B.-W., W.-K. Tao, C.-D. Peters-Lidard, J.-D. Chern, R. Atlas, Y.-L. Lin, R. Reale, , K.-S. Kuo, 2007: Global Mesoscale Modeling on the NASA Columbia Supercomputer: Modulation of Tropical Cyclogenesis by the MJO in May 2002. 3rd Annual NEWS PI Meeting, Huntsville, AL, September 19-21, 2007.
13. Tao, W.-K., J.-D. Chern, C.-D. Peters-Lidard, B.-W. Shen, R. Atlas, S. Lang, J. Luo, G. Stephens, 2007: Evaluation and Improvements of Cloud Model Dynamics and Microphysics in Multi-Scale Modeling System. 3rd Annual NEWS PI Meeting, Huntsville, AL, September 19-21, 2007.
14. Shen, B.-W., W.-K. Tao, R. Atlas, Y.-L. Lin, R. Reale, J.-D. Chern, C.-D. Peters-Lidard, K.-S. Kuo, 2007: Forecasts of Tropical Cyclogensis with a Global Mesoscale Model: Modulation of Six Tropical Cyclones by the MJO in May 2002. CMMAP Team Meeting, Fort Collins, Colorado, August 7-9, 2007.
15. Shen, B.-W., W.-K. Tao, R. Atlas, 2007: Simulations of Multiple Tropical Cyclones with a Global Mesoscale Model: A Preliminary Study on the NASA Columbia Supercomputer. "Research Activities in Atmospheric and Oceanic Modeling" (edited by J. Cote), Report 37, CAS/JSC Working Group on Numerical Experimentation (WGNE) WMO/TD-No. 1397, 6.7-6.8.
16. Shen, B.-W., W.-K. Tao, J.-D. Chern, 2007: Improvements in the Scalability of the NASA Goddard Multiscale Multicomponent Modeling Framework for Hurricane Climate Studies. "Research Activities in Atmospheric and Oceanic Modeling" (edited by J. Cote), Report 37, CAS/JSC Working Group on Numerical Experimentation (WGNE) WMO/TD-No. 1397, 3.17-3.18.
17. Shen, B.-W., W.-K. Tao, R. Atlas, J.-D. Chern, S.-J. Lin, 2007: Multiscale Simulations of a Mei-Yu Front Accompanied by a Drifting Meoscyclone with a General Mesoscale Model. CMMAP Team Meeting, Kauai, Hawaii, February 20-22, 2007.
18. Shen, B.-W., 2006: Hurricane Research. In the section *"Highlights of Laboratory Activities in 2006"* of the annual report "Laboratory for Atmospheres 2006 Technical Highlights", NASA/GSFC.
19. Tao, W.-K., A. Hou, W. Lau, J.-D. Chern, S. Lang, B.-W. Shen, C. Peters-Lidard, R. Shi, X. Li, X. Zeng, S. Kumar, C.-L. Shie, 2006: Applications, Evaluation, and Important of Multi-Scale Modeling Systems. *High-End Computing at NASA*, 40-41.
20. Shen, B.-W., R. Atlas, W.-K. Tao, T. Lee, O. Reale, J.-D. Chern, S.-J. Lin, J. Chang, C. Henze, J.-L. Li, 2006: Experimental High-Resolution Weather/Hurricane Predictions with the NASA fvGCM. *High-End Computing at NASA*, 48-49.
21. Chern, J.-D., W.-K. Tao, C. Peters-Lidard, B.-W. Shen, 2006: Use of a Coupled, Global Cloud-Scale and Land Surface Modeling System to Study the Impact of Land Surface Processes on Energy and Water Cycles. 2nd NEWS PI Meeting, College Park, Maryland, September 26-28, 2006.
22. Shen, B.-W., R. Atlas, O. Oreale, S.-J Lin, J.-D. Chern, J. Chang, C. Henze, 2006: Hurricane Forecasts with a Global Mesoscale-resolving Model on the NASA Columbia Supercomputer Preliminary Simulations of Hurricane Katrina (2005), AGU 2006 Ocean Meeting, Honolulu, Hawaii, February 20-24, 2006.
23. Atlas, R., B.-W. Shen, O. Reale, S.-J. Lin, T. Lee, 2005: Application of NASA's high-resolution finite-volume General Circulation Model (fvGCM) to hurricane prediction. 5th International Scientific Conference on the Global Energy and Water Cycle, Costa Mesa, California, June 20-24, 2005.
24. Shen, Bo-Wen, 2004: Hurricane Forecasting with the NASA's high resolution GCM on the NASA's Columbia Supercomputer. *International Workshop on Monthly-to-Seasonal Climate Prediction.* Taipei, Taiwan. December 13-31, 2004.
25. Atlas, R., B.-W. Shen, O. Reale, J., W. Putman, J., J.-D. Chern, S.-J. Lin, M. Bosilovich, T. Lee, J. Radakovich, K.-S. Yeh, J. Ardizzone, and D. Bungato, 2004: The NASA finite-volume General Circulation Model: The 2004 hurricane season -- a high-resolution NWP application, *The SC2004 High Performance Computing, Networking and Storage Conference*, Pittsburgh, Pennsylvania, November 6-12, 2004.

Outline

- Introduction
- Supercomputing and Concurrent Visualization at NASA
- Global Mesoscale Modeling
  - i. The model
  - ii. Model validations (e.g., Hawaiian Wakes, Mei-Yu fronts)
- Application to High-impact Tropical Weather Prediction
  - i Short-term (5-7 days) Tropical Cyclone Forecasts
    - --- Predictions of Track, Intensity, and Formation
  - ii Extended-range Simulations of Large-scale Tropical Weather
    - --- 15~30-days Simulations of Madden-Julian Oscillations
    - --- 30-days Simulations of 5 African Easterly Waves
- Summary and Conclusions

"A Cycle"

Goals:

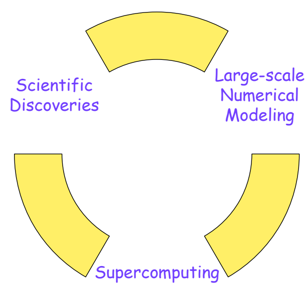
to explore the power of supercomputers on the advancement of numerical weather and hurricane modeling;

to discover how hurricanes form, intensify, and move with advanced numerical models;

to understand the underlining mechanisms (how realistic the model depiction of TC dynamics)

Reducing time to solution by "cooperative interactions"!

(not competing for the same energy!)



Outline

- Introduction
- Supercomputing and Concurrent Visualization at NASA
- Global Mesoscale Modeling
  - i. The model
  - ii. Model validations (e.g., Hawaiian Wakes, Mei-Yu fronts)
- Application to High-impact Tropical Weather Prediction
  - i Short-term (5-7 days) Tropical Cyclone Forecasts
    - --- Predictions of Track, Intensity, and Formation
  - ii Extended-range Simulations of Large-scale Tropical Weather
    - --- 15~30-days Simulations of Madden-Julian Oscillations
    - --- 30-days Simulations of 5 African Easterly Waves
- Summary and Conclusions

Supercomputers @Top 500.org

November, 2007

Japan Earth Simulator (06/2002)

1: IBM/DOE BG/L Beta
2: NASA Columbia
3: Japan ES (11/2004)

Supercomputing at NASA

(November, 2008)

Major Computer systems:

NASA/ARC:

Columbia: SGI Altix, 14,336 cores (Itanium II)

Pleiades: SGI Altix ICE, 47,104 cores (Xeon)

NASA/GSFC

Discover: 6,656 cores, 65 TF Peak (Xeon)

http://www.nas.nasa.gov/SC08/PDF/NCCS08.pdf

The Columbia Supercomputer

(first installed in late 2004)

Based on SGI® NUMAflex™ architecture
20 SGI® Altix™ 3700 superclusters, each with 512 processors
Global shared memory across 512 processors

10,240 Intel Itanium® 2 CPUs
Current processor speed: 1.5 gigahertz
Current cache: 6 megabytes

1 terabyte of memory per 512 processors, with 20 terabytes total memory

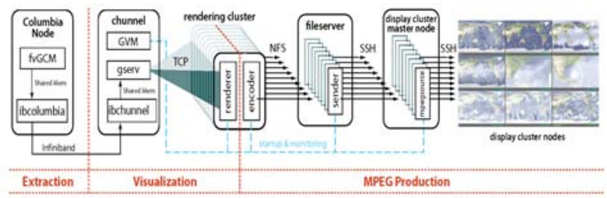
NASA Pleiades Supercomputer

(565 Tflops, ~10x Columbia)

1. **92 Compute Cabinets (64 nodes per cabinet; 2,560 nodes; 2 quad-core processors per node)**
2. **quad-core Xeon 5472 (Harpertown) processors, speed - 3GHz; Cache - 12MB per processor·**
3. **47,104 cores in total (512 cores per cabinet)**
4. **47 TB memory in total, 1 (8) GB memory per core (node)**
5. **450+ TB disk spaces, 1 Lustre cluster-wide filesystem·16 Lustre filesystem server nodes·Nexis 9000 home filesystem·3 DDN 9900 RAIDs**
6. **InfiniBand, 6,400 compute nodes**

http://www.nas.nasa.gov/SC08/PDF/SC08_presskit_handout.pdf

Concurrent Visualization System
(Ellsworth, Green, Henze et al., 2006).



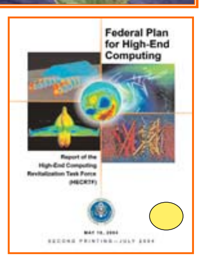
The NASA ARC Concurrent Visualization System. Rounded rectangles indicate systems, and rectangles indicate processes. The whole system (from left to right panels) consists of a computing node ("Columbia node"), a 16-CPU middle-layer system ("Chunnel"), 50 dual-CPU rending cluster, and the hyperwall-1. These systems are used for data extraction, data handling, data visualization and MPEG image production, and visualization display.

128-panel Hyperwall-2

Factors in HW/SW Engineering

To complete 'the cycle', crucial factors include:

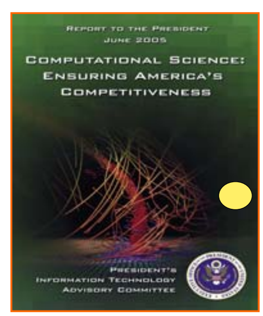
- Scalability, limited by memory bandwidth associated with inherited excessive memory usage in different model components (# of CPUs is not the only factor!)
- Performance, also limited by intensive I/O in ultra-high resolution runs
- "Sustained" performance for a single project (e.g., reduce time to get queues and to run)
- On-line/Off-line mass storages!



``*researchers of the most challenging scientific applications must know the hardware details intimately in order to extract sufficient percentage of the machine's potential performance to render their problem tractable in a reasonable time.*`` (Federal Plan for High-End Computiny, May, 2004)

Computational Science

- An inter-disciplinary filed with the goals of understanding and solving complex problems using high-end computing facilities
- CS is identified as one of the most important filed of the 21st century to contribute to the scientific, economic, social and national security goals of USA by the President's Information Technology Advisory Committee.



June, 2005

Cyber-Enabled Discovery and Innovation (CDI)

- CDI is NSF's bold five-year initiative to create revolutionary science and engineering research outcomes made possible by innovations and advances in ***computational thinking.***
- CDI seeks ambitious, transformative, multidisciplinary research proposals…
- In FY2009: anticipated funding amount: $26M
  estimated number of awards: 30

NSF Program Solicitation: NSF 08-604

Outline

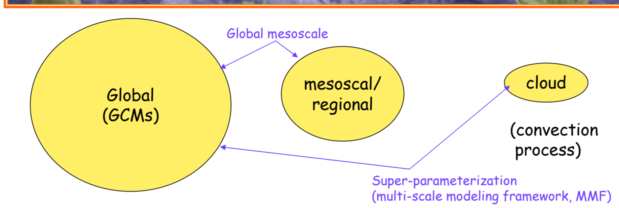
- Introduction
- Supercomputing and Concurrent Visualization at NASA
- Global Mesoscale Modeling
  i. The model
  ii. Model validations (e.g., Hawaiian Wakes, Mei-Yu fronts)
- Application to High-impact Tropical Weather Prediction
  i Short-term (5-7 days) Tropical Cyclone Forecasts
  --- Predictions of Track, Intensity, and Formation
  ii Extended-range Simulations of Large-scale Tropical Weather
  --- 15~30-days Simulations of Madden-Julian Oscillations
  --- 30-days Simulations of 5 African Easterly Waves
- Summary and Conclusions

Why Global Mesoscale Modeling?

Atmospheric modeling activities have been conventionally divided into three major categories based on scale separations, inclusive of synoptic-scale, meso-scale, and micro-scale modeling. However,

- <u>artificial scale separation</u> limits scale interactions and scale transition / cascading;
- Among major sources of weather forecasting errors are <u>insufficient resolution</u> to resolve fine-scale structure in GCMs, and <u>inaccurate information imposed at lateral boundaries</u> in mesoscale models.

Modeling on Different Scales

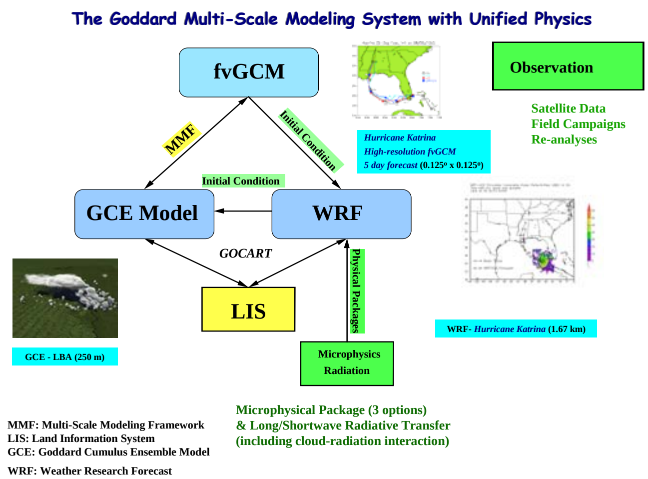


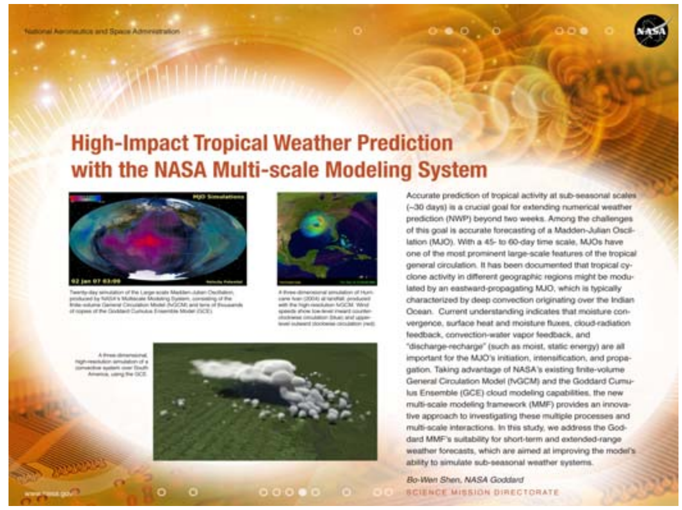
Deterministic ⟷ stochastic

Control ⟷ feedback/responses

Downscaling ⟷ upscaling

integration → scientific discoveries





General Issues in Global Mesoscale Modeling

- Hydrostatic vs. non-hydrostatic (resolved scale ~ 10km, Pielke 2002, Shen 1992)
- Cumulus Parameterizations (validity at a mesoscale resolution? Validity for TC formation?)
- (Additional) Required Physical Processes (e.g., surface flux exchange for TC formation and intensification)?
- Added skill in weather simulations?

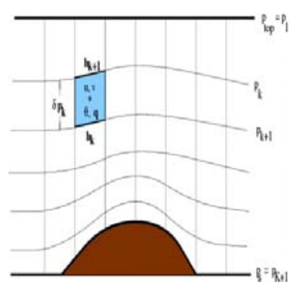
Outline

- Introduction
- Supercomputing and Concurrent Visualization at NASA
- Global Mesoscale Modeling
  - i. The model
  - ii. Model validations (e.g., Hawaiian Wakes, Mei-Yu fronts)
- Application to High-impact Tropical Weather Prediction
  - i Short-term (5-7 days) Tropical Cyclone Forecasts
    - --- Predictions of Track, Intensity, and Formation
  - ii Extended-range Simulations of Large-scale Tropical Weather
    - --- 15~30-days Simulations of Madden-Julian Oscillations
    - --- 30-days Simulations of 5 African Easterly Waves
- Summary and Conclusions

The Global Mesoscale Model

- Model dynamics and physics
  (a) The finite-volume dynamical core (Lin 2004);
  (b) The NCAR physical parameterizations, and NCEP SAS as an alternative cumulus parameterization scheme
  (c) The NCAR land surface model (CLM2, Dai et al. 2003)
- Model runtime configuration
- Computational design, scalability and performance

The finite-volume Dynamical Core (Lin, 2004)



- Terrain following Lagrangian control-volume vertical discretization of the basic conservation laws:
  - Mass
  - Momentum
  - Total energy
- 2D horizontal flux-form semi-Lagrangian discretization
  - Genuinely conservative
  - Gibbs oscillation free
  - Absolute vorticity consistently transported with mass dp within the Lagrangian layers.
- Computationally efficient

Physics Parameterizations

- Moist physics:
  -Deep convections: Zhang and McFarlane (1995);
  Pan and Wu (1995, aka **NCEP/SAS**)
  -Shallow convection: Hack (1994)
  -large-scale condensation (Sundqvist 1988)
  -rain evaporation
- Boundary Layer:
  - first order closure scheme
  - local and non-local transport (Holtslag and Boville 1992)
- Surface Exchange:
  - Bryan et al. (1996)

Pan, H.-L., and W.-S. Wu, 1995: Implementing a mass flux convection parameterization package for the NMC medium-range forecast model. NMC office note, No. 409, 40pp. [Available from NCEP].

Timeline of GMM Deployment

- April 2004 : 1/4 degree GMM running on the Columbia Supercomputer
- July 2004: experimentally realtime NWP
- December 2004: the Columbia ranked 2nd
- January 2005: article accepted and *highlighted by AGU*
- Feb (June) 2005: the first 1/8 (1/12) degree run performed
- 2005 hurricane season: MAP-05 project, running operationally 4-times per day
- January 2006: article with 1/8 degree GMM accepted and *highlighted as a pioneering work* (e.g., Prof. Pielke)
- April 2006: Katrina article accepted, *highlighted by AGU and Science magazine*
- June 2007: TC genesis article submitted

Resolutions vs. Model Grid Cells

Resolution	x	y	Grid cells	Date
1° (~110km)	288	181	52 K	2000
0.5° (~55km)	576	361	208 K	2002
0.25° (~28km)	1000	721	721 K	2004
0.125° (~14km)	2880	1441	4.15 M	2005
0.08° (~9km)	4500	2251	10.13 M	2005

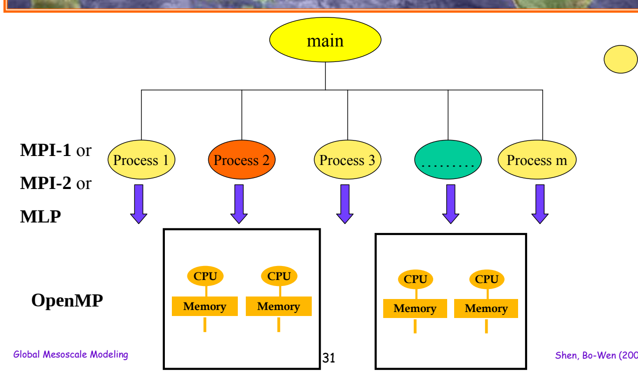
Computational Aspects

Two-level Parallelisms

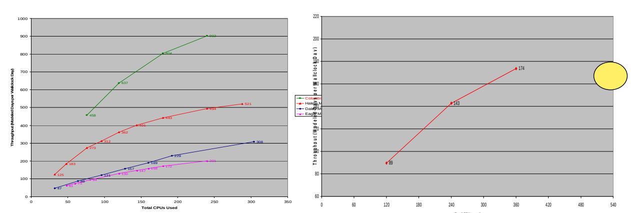
- 1st level: multi-processing:
  - MPI-1 (send/recv),
  - MPI-2*(one-sided communication, put/get)
  - MLP (Unix native system calls, "mmap", "fork", and synchronization)
- 2nd level: multi-threading (on loops)

*GMM is one of "first" GCMs implemented with the MPI-2.

Two Level Parallelism



GMM d32 and e32 NWP Throughput (in late 2004)



As of July, 2006, it takes about 5-h for a 5day forecast with the GMM with 0.08°x0.08°x48L using 1440 CPUs.

Application: Numerical Weather Prediction

Runtime Configurations:

- 0.25x0.36 degree horizontal resolution
- 32 Vertical levels
- 23 million points (1000 x 721 x 32)
- 15 minute timestep for physics
- 45 seconds timestep for dynamics
- NOAA OI (1 degree) weekly SST
- NCEP GFS (T254 or T382) data as dynamic IC
- Twice daily quai- realtime 5-day (10-day) forecasts. 70 GB data set per day

Outline

- Introduction
- Supercomputing and Concurrent Visualization at NASA
- Global Mesoscale Modeling
  i. The model
  ii. Model validations (e.g., Hawaiian Wakes, Mei-Yu fronts)
- Application to High-impact Tropical Weather Prediction
  i Short-term (5-7 days) Tropical Cyclone Forecasts
    --- Predictions of Track, Intensity, and Formation
  ii Extended-range Simulations of Large-scale Tropical Weather
    --- 15~30-days Simulations of Madden-Julian Oscillations
    --- 30-days Simulations of 5 African Easterly Waves
- Summary and Conclusions

The 2004 Hurricane Season

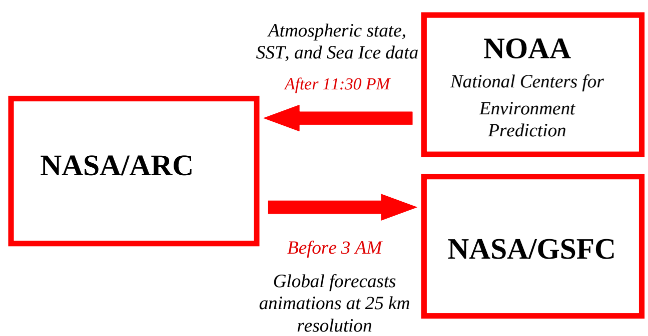
16 named storms

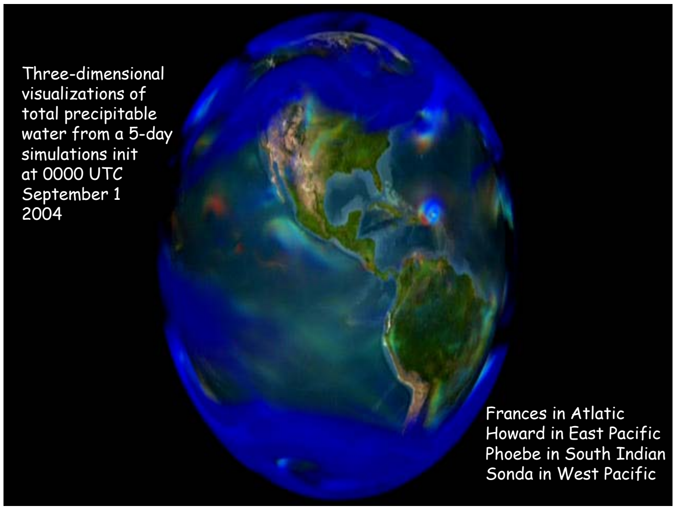
8 hurricanes

6 major hurricanes (cat 3)

#	Name	Date	Wind	Pres	Cat
1	Hurricane ALEX	31 JUL-06 AUG	105	957	3
2	Tropical Depression TWO	03-04 AUG	30	1009	-
3	Tropical Storm BONNIE	09-12 AUG	55	1000	-
4	Hurricane CHARLEY	09-15 AUG	125	941	4
5	Hurricane DANIELLE	13-21 AUG	90	970	2
6	Tropical Storm EARL	13-16 AUG	40		-
7	Hurricane FRANCES	25 AUG-09 SEP	125	935	4
8	Tropical Storm GASTON	27 AUG-01 SEP	60	991	-
9	Tropical Storm HERMINE	29-31 AUG	45	1000	-
10	Hurricane IVAN	02-24 SEP	145	910	5
11	Tropical Depression TEN	09-09 SEP	30	1013	-
12	Hurricane JEANNE	13-28 SEP	110		3
13	Hurricane KARL	16-24 SEP	120	938	4
14	Hurricane LISA	19 SEP-03 OCT	65	987	1
15	Tropical Storm MATTHEW	08-10 OCT	40	997	-
16	Tropical Storm NICOLE	10-11 OCT	45	988	-
17	Tropical Storm OTTO	30 NOV-02 DEC	45	993	-

Daily "Data flow"
Realtime Global Weather Predictions



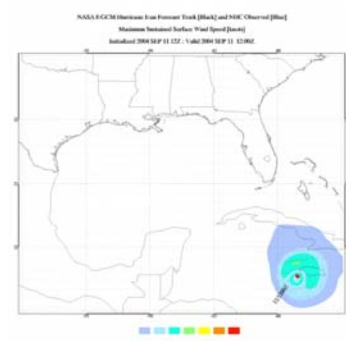


Track Forecast of Hurricane Ivan (2004)

Init at 1200 UTC September 11

Blue: Best Track
Black: Predicted Track

Wind vectors and Wind speeds (shaded)



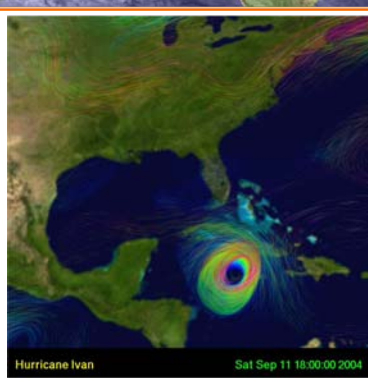
Visualization of Scale interactions

between hurricane Ivan and an upper-level trough

Blue: low-level winds
Red: upper-level winds

Winds show low-level inward counter-clockwise circulation and upper-level outward clockwise circulation.

Before Ivan made landfall, scale interaction between its outflow and an upper-level trough might have been contributed to Ivan's intensification.



Forecasts of Mesoscale Weather Events

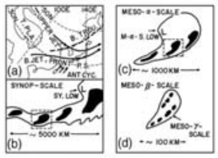
(Validations of the 1/8 degree GMM)

- Hawaiian Wakes (Shen et al. 2006a)
- Catalina Eddy (Shen et al. 2006a)
- Mei-Yu Front (Shen et al. 2007, in preparation)

To show added skills in weather simulations!

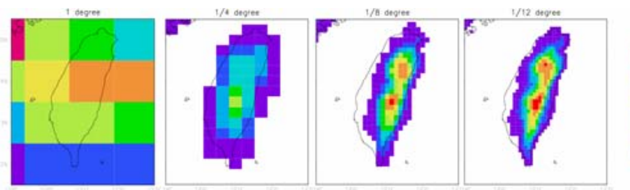
Mei-Yu Front

•extending from southern Japan to southern China during early summer
•quasi-stationary, strong low-level wind shear but a weak temperature gradient
•with embedded organized meso-α- and/or meso-β-scale convective systems, which cause long lasting, heavy precipitation
•with new meso-γ convective cells successively forming in the upstream direction.



Factors of accurate predictions: multi-scale weather phenomena, complicated interactions associated with mechanical and thermal effects of surface forcing in Taiwan and the surrounding area

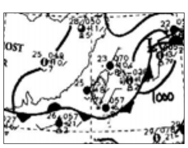
Taiwan's terrains in a 4°x4° box



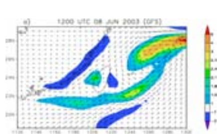
Typical resolutions in climate models:
how can the feedbacks of terrain-induced flows to large-scale circulations be simulated?

Numerical Experiments of a Mei-Yu Front

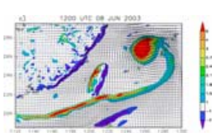
(Acknowledgements: Thanks Drs. C.-P. Cheng, J.-S. Hong, and S.-Y. Chou of the Central Weather Bureau in Taiwan for the help in the surface analysis and radar images)



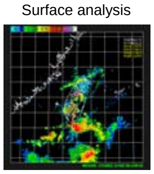
Surface analysis



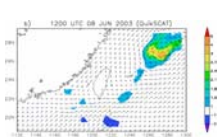
NCEP GFS Analysis



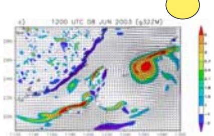
1/8° 48h simulations with SAS



Composite Radar image

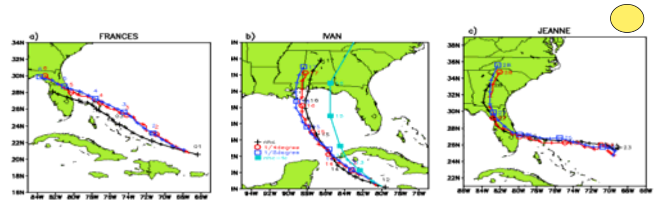


QuikSCAT 0.5° seawinds



1/8° 48h simulations with ZM95

Model Validations on the Forecasts of Hurricane Track (1/4 vs. 1/8 degree)



Five-day track predictions of hurricanes (a) Frances initialized at 0000 UTC 1 Sep., (b) Ivan initialized at 0000 UTC 12 Sep., and (c) Jeanne initialized at 0000 UTC 23 Sep., 2004. The blue (red) lines represent the tracks from 0.125 (0.25) degree simulations, while the black lines represent the best track from the National Hurricane Center. **(Shen et al., 2006a)**

Outline

- Introduction
- Supercomputing and Concurrent Visualization at NASA
- Global Mesoscale Modeling
  - i. The model
  - ii. Model validations (e.g., Hawaiian Wakes, Mei-Yu fronts)
- Application to High-impact Tropical Weather Prediction
  - i Short-term (5-7 days) Tropical Cyclone Forecasts
    - --- Predictions of Track, Intensity, and Formation
  - ii Extended-range Simulations of Large-scale Tropical Weather
    - --- 15~30-days Simulations of Madden-Julian Oscillations
    - --- 30-days Simulations of 5 African Easterly Waves
- Summary and Conclusions

Hurricane Dynamics

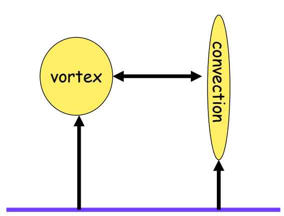
- Movement:
  - steering of large-scale flows
  - impact of beta-drift
- Intensification / formation:
  - 1: small-scale processes: CISK (conditional instability of second kind), WISHE (wind-induced surface fluxes exchange), axisymmetrization, vortex mergers, vortex enhancement
  - 2: large-scale processes: Rossby wave accumulation, inertia stability, modulations by MJO and African Easterly waves, barotropic/baroclinic instability

CISK and WISHE

CISK (Charney and Eliassen 1964; Ooyama 1964,1969,1982):
-> cooperative interaction between a vortex and convection
-> cooperative interaction between primary circulation and secondary circulation

WISHE:
Emanuel (1986) argues that the energy exchange between boundary layer and the ocean is much stronger than suggested by theories relying on ambient CAPE for energy production

Evaporation-Wind-Convection feedback:



Regional model

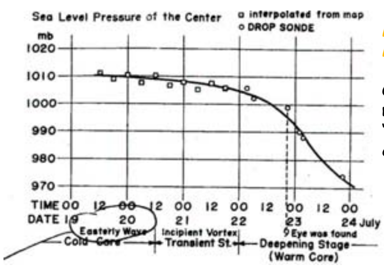
Vortex enhancement and Vortex merger

(Tory et al. 2006a,b,c; Mongonmery et al. 2006))

- Primary vortex enhancement: construction of vortex cores in convective updrafts through horizontal convergence and vertical advection of absolute vorticity
- Secondary vortex enhancement:
  - -diabatic upscale vortex cascade, vortices generated by the above mechanism interacted to form larger (low- to midlevel) vortices
  - -system scale intensification (SSI), the sum of diabatic heating (from condensation) and adiabatic cooling (from expansion in the hot towers) was slightly positive, and the net heating enhanced the system-scale secondary circulation

"*perhaps that explicitly resolving the individual convective processes may not be necessary for qualitative TC genesis forecasts*"
commented by Tory et al. (2006a)

Three Stages of TC Formation (Yanai, 1961)



Modulation By large-scal Flows (MJO, AEW)

Vortex merger/ enhancement; axisymmetrization

WISHE; CISK

Multiscale interaction,
Multiple processes

Challenges: (1) what is the model's limit on mesoscale "predictability"? (2) can computing be affordable?

Parameterizations and Hurricane Modeling

- Cumulus parameterization (CP) is to ``emulate'' the effects of unresolved convection in the latent heat release → Cooperative interaction between a vortex and convection.
- The CP was an important technical factor in the reduction of a multiscale interaction problem to a mathematically tractable form. (Ooyama, 1982)
- CP has a long history in hurricane modeling: Anthes (2003) states "*the late 1950s and early 1060s saw the beginning of serious attempts to model TCs...... The observational studies of Riehl and Malkus showed that the cumulus clouds were essential components of hurricane energetics and so...... CP so dominated the research in the 1950s and 1960s that many people simply referred to the topic as "parameterization"*.
- CP was used to stabilize numerical integrations by Kasahara, who (2000) stated "*The origin of CP is traced as a necessary means to perform stable time integrations of the PE model with moist physical processes*", which is different from usual.

Issues with Cumulus Parameterizations

- The cloud parameterization problem is ``deadlocked'' in the sense that our rate of progress is unacceptably slow (Randall et al.,2003)
- In spite of the accumulated experience over the past decades, however, cumulus parameterization is still a very young subject (Arakawa, 2004).
- The performance of parameterization scheme can be better understood if one is not bound by their authors' justifications (Arakawa, 2004).
- CP has problems for grid spacing between 3 and 25km (e.g., Molinari and Dedek, 1992); CP is not good for studying TC genesis!

WISHE and surface/boundary layer parameterizations

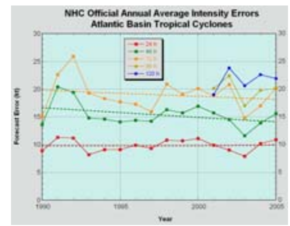
- Energy sources: from the ocean
- Role of convection: redistribution of heat and moistures
- However, drag coefficients are not well known (e.g., Powell et al., 2003; Yi et al., 2007; at extreme wind speeds, Emanuel 2003 found that exchange coefficients should become independent wind speed in high wind limits)

Outline

- Introduction
- Supercomputing and Concurrent Visualization at NASA
- Global Mesoscale Modeling
  - i. The model
  - ii. Model validations (e.g., Hawaiian Wakes, Mei-Yu fronts)
- Application to High-impact Tropical Weather Prediction
  - i Short-term (5-7 days) Tropical Cyclone Forecasts
    - --- Predictions of Track, Intensity, and Formation
  - ii Extended-range Simulations of Large-scale Tropical Weather
    - --- 15~30-days Simulations of Madden-Julian Oscillations
    - --- 30-days Simulations of 5 African Easterly Waves
- Summary and Conclusions

Progress of Hurricane Forecasts
(National Hurricane Center)

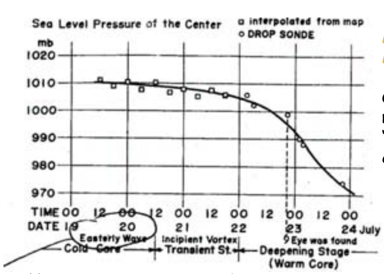
Track forecasts have been steadily improving.



Intensity forecasts have lagged behind.

http://www.nhc.noaa.gov/verification/figs/OFCL_ATL_int_error_trend.gif

Three Stages of TC Formation
(Yanai, 1961)



Modulation By large-scal Flows (MJO, AEW)

Vortex merger/ enhancement; axisymmetrization

WISHE; CISK

Multiscale interaction, Multiple processes

Challenges: (1) what is the model's limit on mesoscale "predictability"? (2) can computing be affordable?

The 2005 Atlantic Hurricane Season

http://www.nhc.noaa.gov/tracks/2005atl.gif

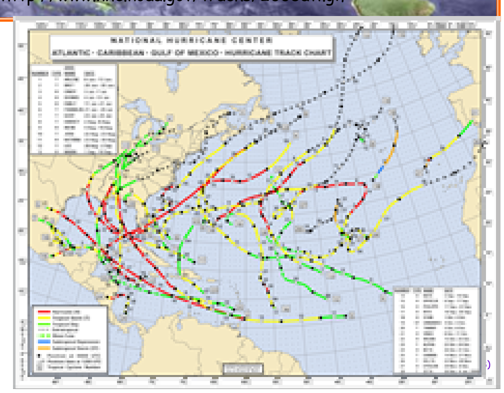
28 stormed (27 named)

15 hurricanes

7 cat-3+ hurricanes

4 cat-5+ hurricanes (Emily, Katrina, Rita. Wilma)

Total damage: $128 billion



Hurricane Katrina (2005)

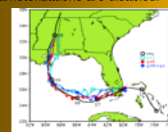
- •Cat 5, 902 hPa, with two stages of rapid intensification
- •The sixth-strongest Atlantic hurricane ever recorded.
- •The third-strongest landfalling U.S. hurricane ever recorded.
- •The costliest Atlantic hurricane in history! ($75 billion)

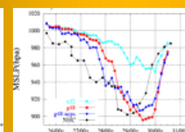
http://en.wikipedia.org/wiki/Hurricane_Katrina

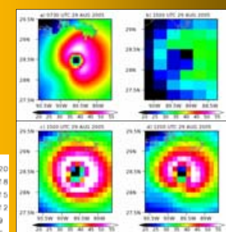
Forecasts of Katrina's Track, Intensity, Structures

•It is known that General Circulation Models (GCMs) have insufficient resolution to accurately simulate hurricane near-eye structure and intensity. Their physics packages (e.g., cumulus parameterizations) are also known limiting factors in simulating hurricanes.

•Six 5-day simulations of Katrina at both 0.25° and 0.125° show comparable track forecasts, but the higher-resolution (0.125°) runs provide much better intensity forecasts, producing the center pressure with errors of only +- 12 hPa. Realistic near-eye wind distribution and vertical structure are also obtained as cumulus parameterizations are disabled.

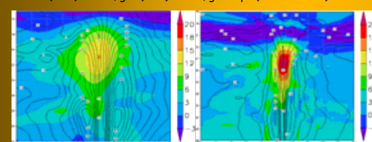






Near-eye Wind Distributions in a 2°x2° box (a) AOML high-resolution surface wind analysis, (b) the 0.25° 99h simulations, (c) the 0.125° 99h simulations, (d) the 0.125° 96h simulations without convection parameterizations (CPs).

Landfall errors:
e32 (1/4°): 50km, g48(1/8°): 14km, g48ncps (1/8° w/o CPs): 30km

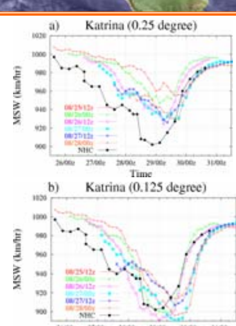


GFS Analysis (~35km) valid at 08/29/12z

96 h Simulations with no CPS

High-resolution runs simulate realistic intensity, RMW (radius of max wind) and warm core (shaded)

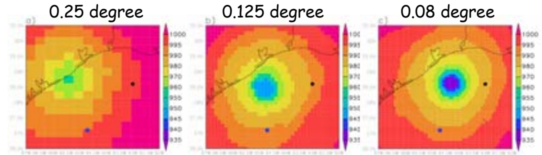
Katrina Intensity Forecasts



Simulations of Hurricane Rita (2005)

Four-day forecasts of the Hurricane Rita initialized at 0000 UTC September, 21, 2005.

• Top panel: Tracks predicted at 1/4° (green), 1/8° (yellow), and 1/12° resolution (red). The black and blue lines represent the observation and official prediction by the National Hurricane Center (NHC). Bottom Panel: Sea level pressure (SLP, unit:hpa) in a 4°x5° box at 72h simulations. '•' and '■' indicate the observed and official predicted locations by the NHC, respectively.



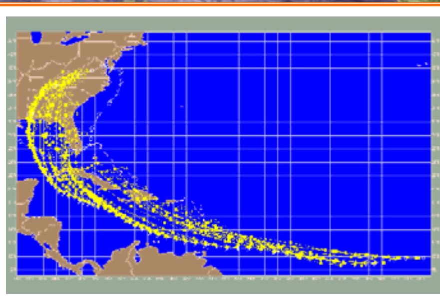
Bbserved MSLP: 931 hpa.

Outline

- Introduction
- Supercomputing and Concurrent Visualization at NASA
- Global Mesoscale Modeling
  - i. The model
  - ii. Model validations (e.g., Hawaiian Wakes, Mei-Yu fronts)
- Application to High-impact Tropical Weather Prediction
  - i Short-term (5-7 days) Tropical Cyclone Forecasts
    - --- Predictions of Track, Intensity, and Formation
  - ii Extended-range Simulations of Large-scale Tropical Weather
    - --- 15~30-days Simulations of Madden-Julian Oscillations
    - --- 30-days Simulations of 5 African Easterly Waves
- Summary and Conclusions

Hurricane Forecasts with CPs disabled

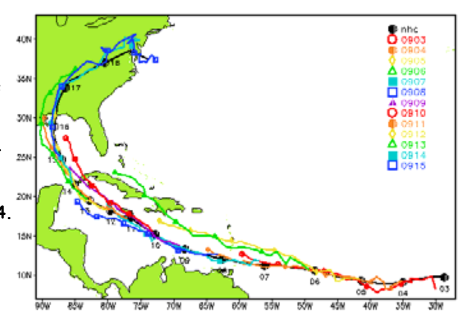
NHC Official Forecasts of Hurricane Ivan (2004)



Note: a persistent right of track bias

Exploring No-Man's Land
(Forecasts of Ivan, 2004)

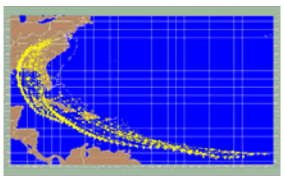
13 consecutive 5-day track forecasts of hurricane Ivan (2004), initialized at 0000 UTC September 03-15, 2004.



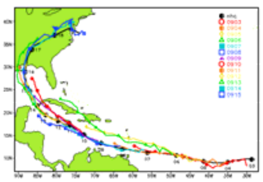
Black: best track;
Each color line: a 5-day track forcasts

Track Forecasts of Ivan (2004)

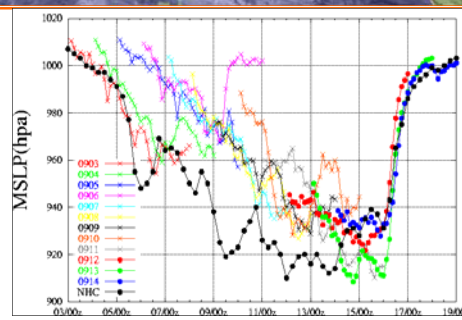
NHC official forecasts



NASA high-resolution GCM



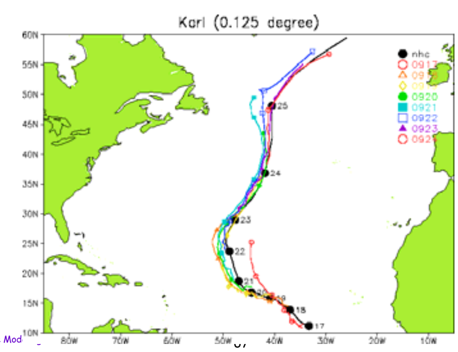
Intensity Forecasts of Hurricane Ivan (2004)



Realistic intensification rate!

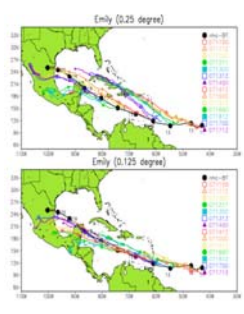
Track Forecasts of Karl (2004)

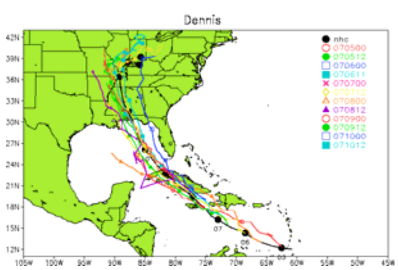
(8 consecutive 5-day forecasts)



Track Forecasts of Emily and Dennis(2005)

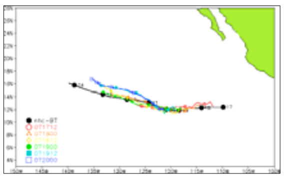
(14 and 12 consecutive 5-day forecasts, respectively)





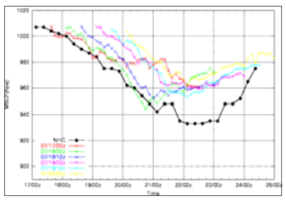
Shen et al. (2006b,c)

Hurricane Daniel (2006)



Six consecutive 5-day forecasts

Features of Annular Hurricanes:
1) axisymmetry
2) rapid intensification
3) slow weakening



Experiments with disabled CPs

- Improvements in track forecasts and more realistic intensity (vertical structure) were obtained for intense hurricanes in 2004 and 2005 (60+ 5-day forecasts were performed, Shen et al., 2006c)
- Why? *Tripoli (1992): ….so the debate comes one of whether the parameterized approach, which assumed subgrid scale cumulus ensembles with clouds of assumed simplistic structures, is more realistic or whether explicitly predicted *convective overturning* on the scale of mesoscale convection system rather than individual plumes is more realistic*

TC Intensification with no CPs

- Rothenhal 1979: 20km, realistic intensity
- Molinari and Dudek (1992): "explicit approach (at a 10-20km grid spacing) made it possible to interpret mature hurricane structure while avoiding arbitrary assumptions of CPs."
- Riehl, 1950: "*condensation energy is converted into kinetic energy not through local overturning of a vertically unstable atmosphere, but through large-scale vertical circulation*" → effects of latent heat need to be projected at the (vortex) scale of the vertical circulation.
- Preliminary analyses indicate with CISK (SSI) is important as convection is better resolved at finer resolutions. In addition, analyses with a focus on the performance of surface and boundary layer parameterizations suggest that WISHI seems to be applicable to our cases.

Outline

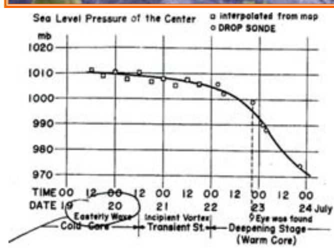
- Introduction
- Supercomputing and Concurrent Visualization at NASA
- Global Mesoscale Modeling
  - i. The model
  - ii. Model validations (e.g., Hawaiian Wakes, Mei-Yu fronts)
- Application to High-impact Tropical Weather Prediction
  - i Short-term (5-7 days) Tropical Cyclone Forecasts
    - --- Predictions of Track, Intensity, and Formation
  - ii Extended-range Simulations of Large-scale Tropical Weather
    - --- 15~30-days Simulations of Madden-Julian Oscillations
    - --- 30-days Simulations of 5 African Easterly Waves
- Summary and Conclusions

Challenges of TC Genesis Forecasts

- Montgomery and Farrell (1993) and others have pointed out neither the CISK nor WISHE theories are appropriate descriptions of the tropical cyclogensis process

- *The major unresolved problem in tropical cyclogenesis thus becomes one of understanding how a weak-amplitude tropical disturbance is transformed into a surface vortex sufficient strength that can amplify via the WISHE process* (➔vortical hot tower, vortex merger)

Three Stages of TC Formation (Yanai, 1961)



Modulation By large-scal Flows (MJO, AEW)

Vortex merger/ enhancement; axisymmetrization

WISHE; CISK

Ooyama (1982): "… **synoptic conditions** do not directly determine the processes of genesis, but may certainly affect the probability of its happening. With a better understanding of the **mesoscale dynamics of organized convection**, the range of statistical uncertainty can be narrowed down."

Ooyama (1969): "under the assumption of axisymmetry, *it is not possible to consider the movement of the cyclone center or to investigate the interaction of the cyclone with the synoptic environment.*"

Effects of Large-scale Flows

- Modulations of TCs by MJOs
- Modulations of TC by African easterly waves
- Scale interactions between vortices and a monsoon trough

MJO and TC genesis

• The MJO, also referred to as the 30-60 day or 40-50 day oscillation, turns out to be the main intra-annual fluctuation that explains weather variations in the tropics. The MJO affects the entire tropical troposphere but is most evident in the Indian and western Pacific Oceans.

•The modulation of TC activity by the MJO in different regions was documented by Liebmann et al. (1994), Maloney and Hartmann (2000).

• Twin TCs, straddling the equator at low latitudes, occasionally may occur in the Indian Ocean and West Pacific Ocean (e.g., Lander 1990).

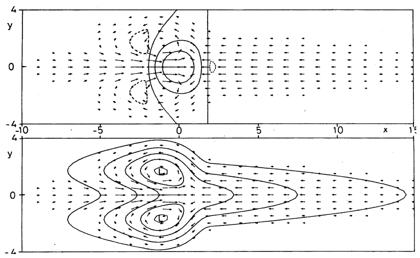
Equatorial Rossby Waves

Gill's solutions (1980)

Solution for idealized heating symmetric to the equator

(a) Vertical velocity superimposed on the low-level winds

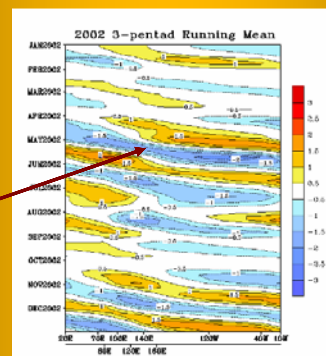
(b) Perturbation pressure



It has been hypothesized that the occurrence of the MJO could represent a crucial precursor to TC genesis.

2002 MJO

May 2002

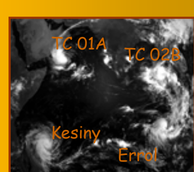


Pentad mean NCEP/CPC MJO indices for 2002. The negative values represent the MJO related convection center propagation Eastward. The values are normalized. (Zhang et al., 2007)

0630 UTC 1 May 2002

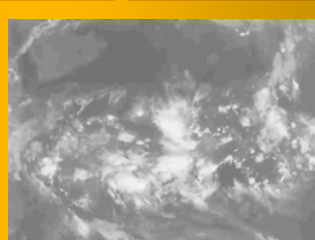
0630 UTC 6 May 2002

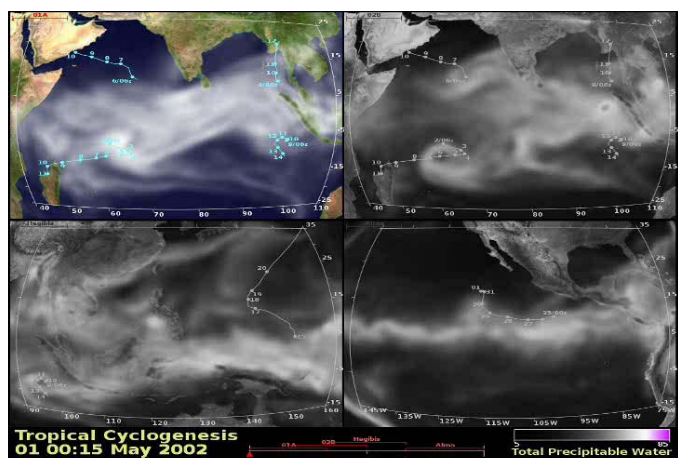
0630 UTC 9 May 2002



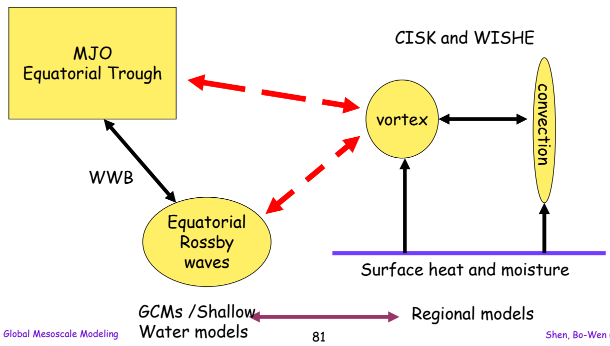
- Two pairs of twin TCs appeared sequentially after an Madden-Julian Oscillation (MJO) propagated eastward through these areas.

Kesiny (3-11) and TC 01A (6-10, May)
Errol (9-14) and TC 02B (9-12 May)
Supertyphoon Hagibis (15-21 May)
Hurricane Alma (25 May – 1 June)





A unified view on TC genesis



Some notes on Scale Transition

- During the processes of TC intensification, (local) Rossby radius of deformation is reduced, energy trapping associated heating is more efficient, (namely less energy carried outward by propagating gravity waves via the geostrophic/gradient-wind adjustment)
- "scale separation" is reduced as the inertial instability increases -> individual clouds become more and more under the control of the balanced dynamics
- Molinari and Dedek (1992, p 329): *Ooyaman noted that it was this characteristic that allowed the success of CP in numerical simulation of mature hurricanes*
- $L_R=NL/(vor+f)^{1/2}(2V/R+f)^{1/2}$

Comments on Vortex Merger and Axisymmetrization

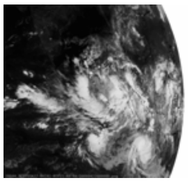
- Nolan (2007a): `` *the idea that vortex merger is critical to the structure changes that lead to genesis is not supported by these simulations*''.
- Nolan et al. (2007b, JAS): `` *the final change in the vortex strength does not depend on the temporal distribution of the heating*'' (during the heat release, asymmetries extract a large amount of energy from the vortex. After a period of significant heating, the asymmetries return energy to the vortex during axisymmetrization.)
- Luo and Liu (2007, JGR), studying the process of axisymmetrization in a triple-scale system, concluded that `` *the kinetic energy of the inner area of the vortex is almost monotonically increased without the subtropical ridge while it is increased irregularly with the subtropical ridge incorporated*.''

Application: TC Nargis (2008)

- Deadliest named cyclone in the North Indian Ocean Basin
- Short lifecycle: 04/27-05/03, 2008; identified as a degression at 04/27/03Z by the IMD; as TC01B at 04/27/12Z by the JTWC
- Very intense, with a MSLP of 962 hPa and peak winds of 135 mph (~CAT 4)
- High Impact: damage ~ $10 billion; fatalities ~ 134,000
- Affected areas: Myanmar (Burma), Bangladesh, India, Srilanka

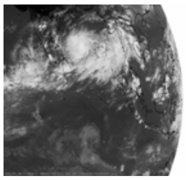
Very Severe Tropical System Nargis (2008)

00Z Apr 22



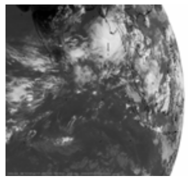
Durga (22-24 Apr) Rosie (21-24 Apr)

12z Apr 27



Formation of Nargis

11z May 2



Landfall in Myanmar

Working Hypotheses

- Previous studies with the global mesoscale model suggest that the genesis of this kind of TCs in the Indian Ocean, which include two pairs of twin TCs in May 2002, can be predicted 2~3 days in advance (Shen et al., 2007, in revision)
- The westerly wind burst (WWB) associated with a weak MJO might be a precursor to the genesis of TC Nargis (2008). Moreover, the asymmetry of the WWB and the MJO can cause the asymmetry of the formation in location for a pair of TCs with a time lag, as indicated by two TCs appeared earlier in the Southern Hemisphere. ===> importance of simulating the latitude variations of WWB (e.g., northward movement) associated with the equatorial trough
- Accurate simulations of the WWB and its impact (e.g., moisture transport) and multiscale interactions are crucial for the prediction of the Nargis formation.

Riehl's (1948) Conceptual Model

in the trade

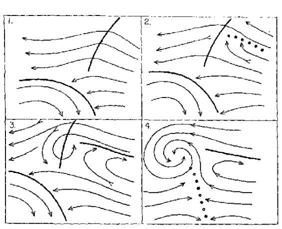


FIG. 16. Model of four stages during typhoon formation in the low troposphere, when the development takes place in the northern-hemisphere trade.

in the equatorial westerlies

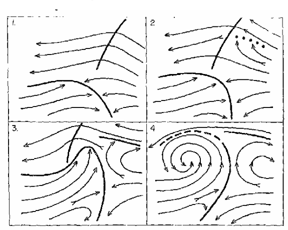
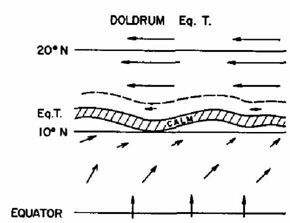


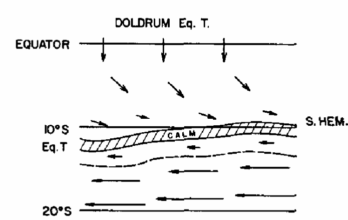
FIG. 17. Model of four stages during typhoon formation in the low troposphere, when the development takes place in the equatorial westerlies.

The Impact of Equatorial Trough (Gray, 1968)

Northern Hemisphere



Southern Hemisphere



Eq. T: Equatorial Trough

------- Location of Disturbance and TC Genesis

Dynamic Instability and Enhanced Monsoonal Circulation

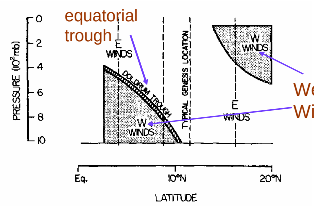


FIG. 26. Schematic north–south cross section of zonal winds relative to the position of a doldrum or monsoon equatorial

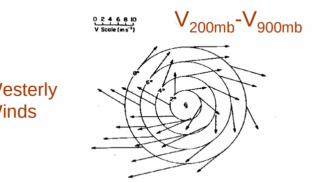


FIG. 3.7. Vertical wind shear vectors ($V_{200mb} - V_{900mb}$) in developing tropical disturbances. (Constructed using data in Figs. 34 and 35 of McBride, 1979.) Circles denote radial distances in degrees of latitude from center of disturbance.

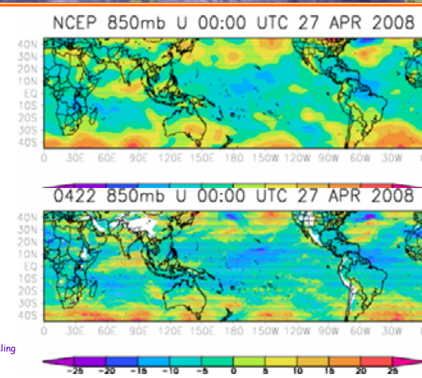
McBride and Zehr (1981) stated:

- Cyclogenesis takes place under conditions of zero vertical wind shear near the system center.
- There is a requirement for large positive zonal shear to the north and negative zonal shear close to the south of a developing system. There also is a requirement for southerly shear to the west and northerly shear to the east. The scale of this shear pattern is over a 10° latitude radius circle with maximum amplitude at ~6° radius. ==> anti-cyclonic wind shear

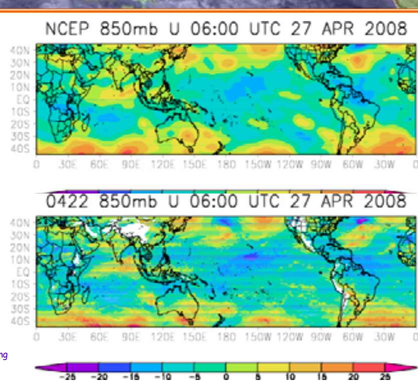
120h Simulations init at 00z Apr 22

NCEP

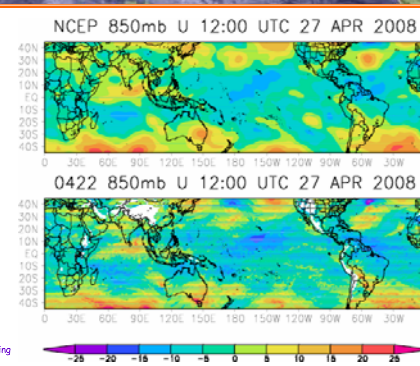
GMM

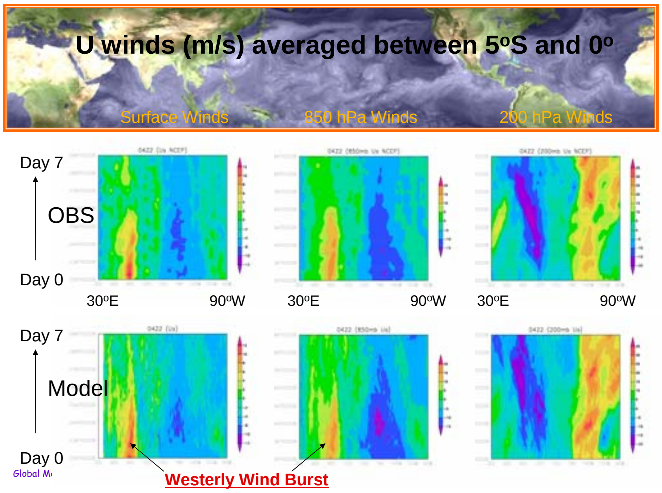


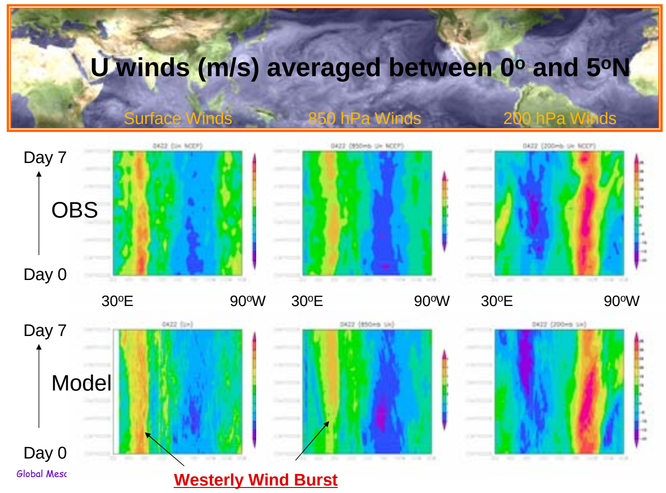
126h simulations

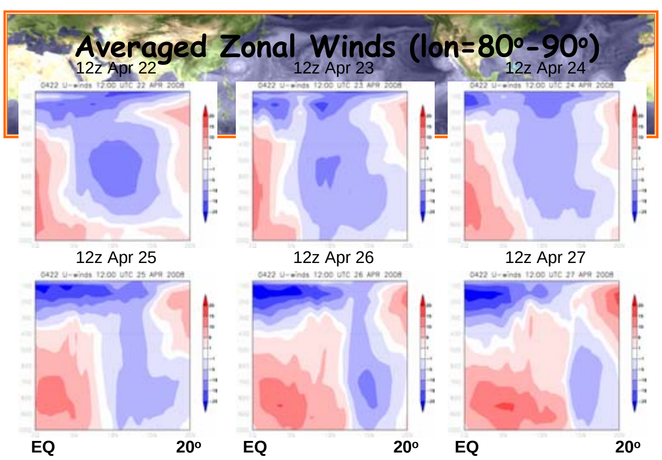


132h simulations

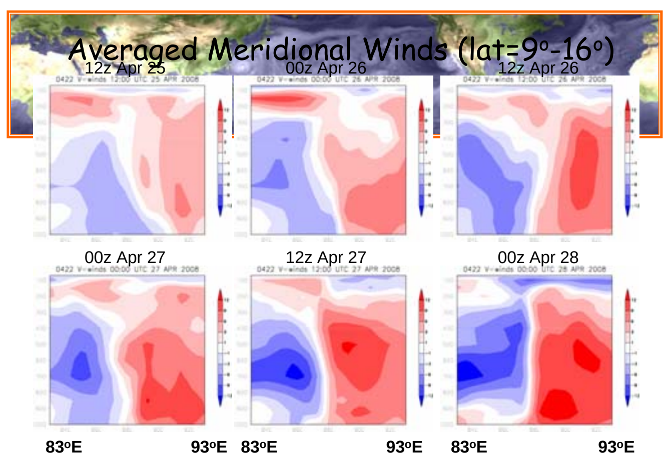








Red: Westerly Winds; Blue: Easterly Winds



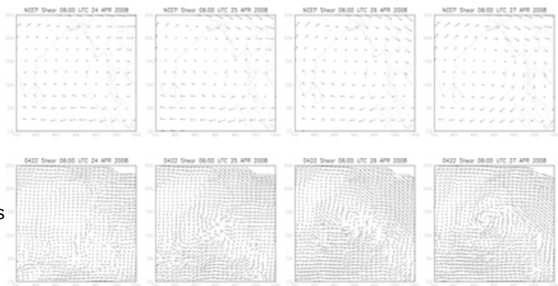
Red: Southerly Winds; Blue: Northerly Winds

$V_{200hpa} - V_{850hpa}$

06z Apr 24 | 06z Apr 25 | 06z Apr 26 | 06z Apr 27

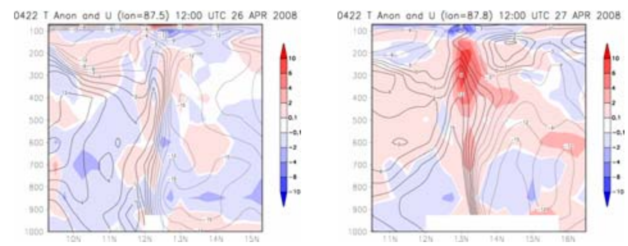
NCEP 2.5ºx2.5º Analysis

Forecasts (skip,3)



54h | 78h | 102h | 126h

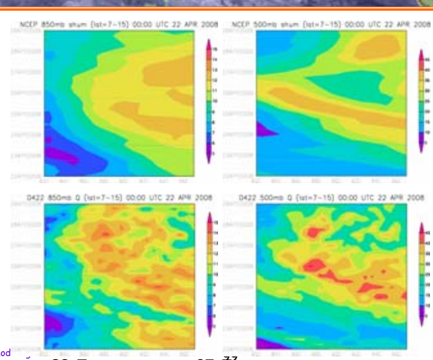
Temperature Anomaly and U winds



108h simulations | 132h simulations

Verifications of Simulated Water Vapor

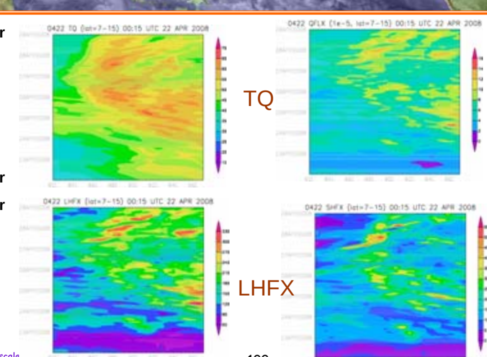
850 hpa | 500 hpa



NCEP Reanalysis (2.5ºx2.5º)

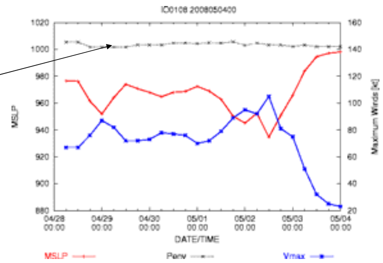
Model (0.25ºx0.36º)

Moist Processes



Satellite Observations and Model Analysis

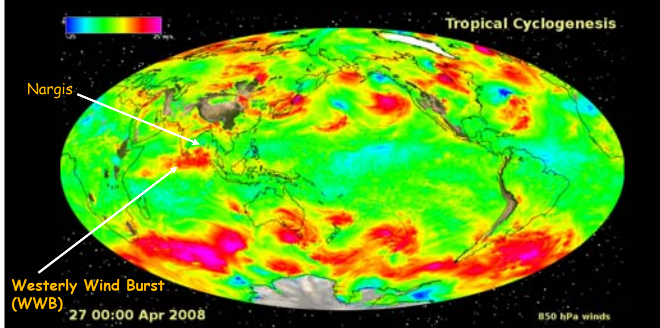
NCEP Analysis



http://rammb.cira.colostate.edu/products/tc_realtime/products/MPSWMSLP/2008IO01_MPSWMSLP_200805040000.GIF

Note: During the life cycle of Nargis, minimum SLP in the analysis remains nearly 1000 hPa!

Formation of TC Nargis from 120h Simulations

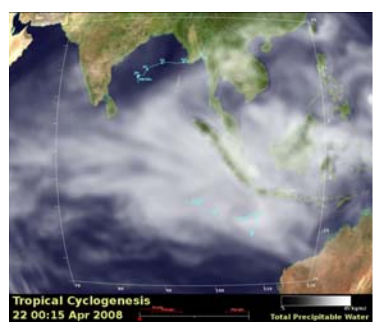


Favorite factors for the formation of TC Nargis

- (Leading edge of) the WWB (fig. 2)
- (North of) the equatorial trough (fig. 3)
- Enhanced monsoonal circulation (fig. 3)
- Zero wind shear line (fig. 3)
- A good upper-level outflow (fig. 4)
- Anti-cyclonic wind shear (200 - 850 hPa, fig. 4)
- Low- and middle-level moistening (fig. 5)
- Surface fluxes (fig. 5)

Shen, B.-W. and W.-K Tao, 2008:Tropical Cyclogenesis Revealed in Global Mesoscale Simulations: Very Severe Cyclonic Storm Nargis (2008). (in preparation, presented in the poster form at CMMAP and SC2008)

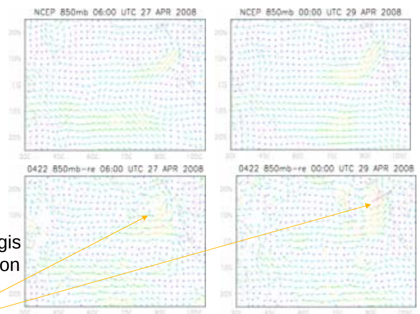
7-days simulations of TC Nargis (2008)



Forecasts vs. Reanalysis (850 hPa Winds)

NCEP Re-Analysis (viewed as “observations”)

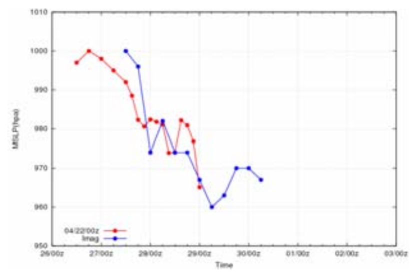
Model Forecasts at Day 5 and Day 7, showing realistic Nargis counter-wise circulation



Nargis

Day 5 Day 7

Simulated Intensity Evolution of TC Nargis (2008) (from Day-5 to Day-7)



The run was initialized at 0000 UTC April 22, 2008. TC Nargis was first reported at 1200 UTC April 27, 2008.

Outline

- Introduction
- Supercomputing and Concurrent Visualization at NASA
- Global Mesoscale Modeling
  - i. The model
  - ii. Model validations (e.g., Hawaiian Wakes, Mei-Yu fronts)
- Application to High-impact Tropical Weather Prediction
  - i Short-term (5-7 days) Tropical Cyclone Forecasts
    - --- Predictions of Track, Intensity, and Formation
  - ii Extended-range Simulations of Large-scale Tropical Weather
    - --- 15~30-days Simulations of Madden-Julian Oscillations
    - --- 30-days Simulations of 5 African Easterly Waves
- Summary and Conclusions

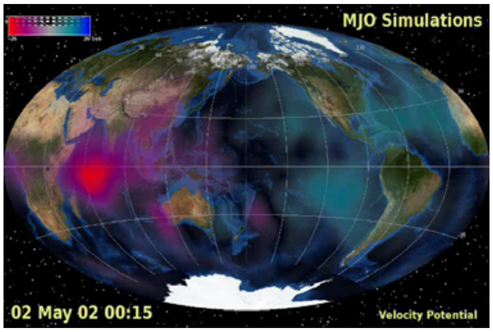
Weather to short-term Climate

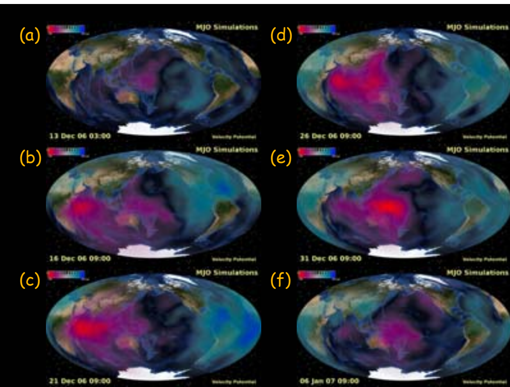
Weather	⟷	Climate
IVP (initial value problem)		BVP (boundary value problem)
Analytic		Asymptotic
Resolving		Parameterization

How to Extend the model’s predictive capabilities?
(what’s the “predictabilitiy” on different scales?)
→Where is the borderline for solving an IVP and a BVP?
Accuracies of initial conditions and numerical schemes, fine grid spacing,
Appropriate emulation of unresolved processes (convection, surface layer)

15-day Simulations of an MJO in 2002

B.-W. Shen, W.-K. Tao, J.-D. Chern, C. D. Peters-Lidard, J.-L. Li, 2008: Extended-Range Predictions of Madden-Julian Oscillations with the Goddard Multi-scale Modeling System (in preparation, presented at the CMMAP and AMS2009)





A 30-day simulation of an MJO initialized at 0000 UTC December 13, 2006, as shown in 200 hpa velocity potential. This MMF simulation captures several major features usually associated with an MJO: (1) initiation of large-scale organized convection in the Indian Ocean in panel (b), (2) intensification as shown in panel (c), (3) slow propagation (prior to reaching the Maritime continent), (4) followed by fast propagation, and (5) weakening. However, this simulated MJO also produces stronger vertical motion than does the NCEP/GSF reanalysis.

Outline

- Introduction
- Supercomputing and Concurrent Visualization at NASA
- Global Mesoscale Modeling
  - i. The model
  - ii. Model validations (e.g., Hawaiian Wakes, Mei-Yu fronts)
- Application to High-impact Tropical Weather Prediction
  - i Short-term (5-7 days) Tropical Cyclone Forecasts
    - --- Predictions of Track, Intensity, and Formation
  - ii Extended-range Simulations of Large-scale Tropical Weather
    - --- 15~30-days Simulations of Madden-Julian Oscillations
    - --- 30-days Simulations of 5 African Easterly Waves
- Summary and Conclusions

African Easterly Waves

- During the summer time (from June to early October), African easterly waves (AEWs) appear as one of the dominant synoptic weather systems in West Africa.
- These waves are characterized by an average westward-propagating speed of 11.6 m/s, an average wavelength of 2200km, and a period of about 2 to 5 days.
- It has been documented that some AEWs could develop into hurricanes in the Atlantic and even East Pacific regions (e.g., Carlson, 1969). These hurricanes, which are usually intense, are called "Cape Verde" storms.
- In addition, studies also suggested that AEWs could modulate the features of the Inter-Tropical Discontinuity (ITD) over the African continent (e.g., Berry and Thorncroft, 2005 and references therein), where the African northeasterly trade winds and southwesterly monsoon flows meet.
- Therefore, improving our understanding and predictions of the **West African rainfall and hurricane formation** in the Atlantic would rely on the accurate simulations of the AEWs.

Map of North Africa

Berry and Thorncroft (2005, MWR)

10°W 0° 10°E 20°E 30°E 40°E

20°N

10°N

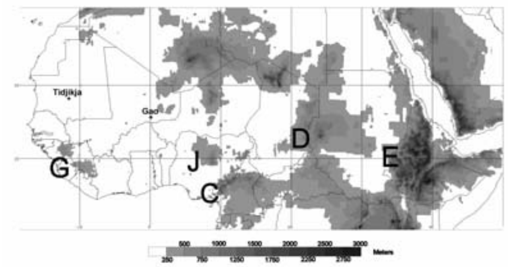
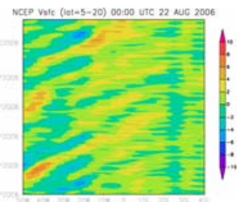


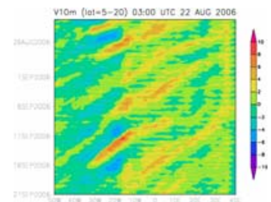
FIG. 1. Map of North Africa, including coastline and national borders. Relief over 250 m is shaded, with key at the bottom of the figure. Labels on the western side of orography identify the following regions: G = Guinea highlands, J = Jos Plateau, C = Cameroon highlands, D = Darfur highlands, and E = Ethiopian highlands. Locations of synoptic observations are marked by a cross and labeled with the station name.

Five AEWs in 30-day Simulations
(init at 00zz Aug 22, 2006)

NCEP (Reanalysis) High-res GCM

22 Aug





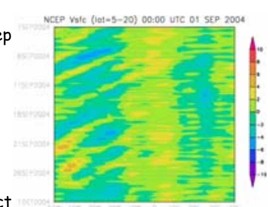
21 Sep

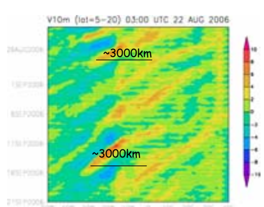
50°W 40°E

AEWs in 30-day Simulations
(init at 00zz Sep 01, 2004)

NCEP (Reanalysis) High-res GCM

01 Sep



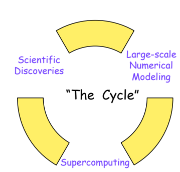


01 Oct

50°W 40°E

Summary

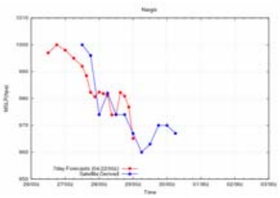
- Improved forecasts of TC track, intensity and formation with the improved high-resolution global model
- Improved extended-range (15~30 -days) simulations of MJOs and AEWs.
- A unified view on TC formation, including modulation of large-scale flows (e.g., MJO) and interaction between mesoscale vortices, surface fluxes and convection.
- Future work: extending the current approach to study hurricane climate and impact of global warming on hurricane climate.

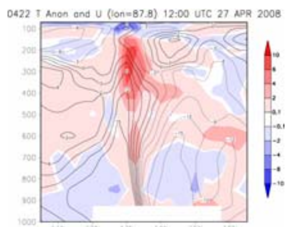


- NASA Global Mesoscale Model: one of the first ultra-high resolution GCMs
- NASA Multi-scale Model Framework: consisting of the NASA global model and tens of thousands of copies of NASA cloud resolving model (GCE)
- An approach with explicitly-resolved convection and/or its effects to reduce the uncertainties of cumulus parameterizations
- Model Validations with mesoscale weather systems such as the Catalina Eddy, Hawaiian Wake, Mei-Yu front etc

Columbia: SGI Altix, 14,336 cores (Itanium II)
Pleiades: SGI Altix ICE, 47,104 cores (Xeon)
Hyperwall-2: 128 panels

Predictions of TC Nargis Formation
(7-day forecasts init at 00Z Apr 22)





Shen, B.-W. and W.-K Tao, 2008:Tropical Cyclogenesis Revealed in Global Mesoscale Simulations: Very Severe Cyclonic Storm Nargis (2008). (in preparation, presented in the poster form at CMMAP and SC2008)

Reality vs. Certainty

As far as the laws of mathematics refer to reality, they are not certain; and as far as they are certain, they do not refer to reality (Albert Einstein)

Reductionism???

High-resolution modeling

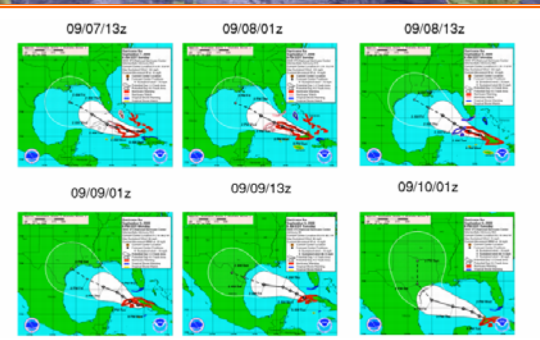
Analytic vs. Asymptotic (weather, climate)

Resolving vs. Parameterization (1D, 2D, 3D)

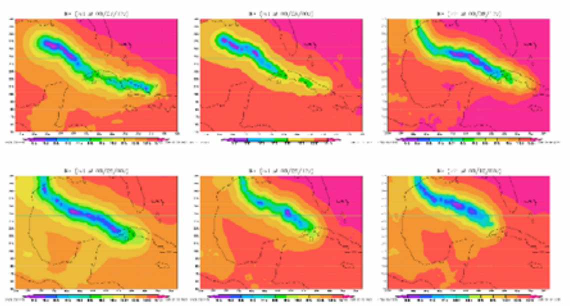
Downscaling vs. Upscaling

Control/Feedbacks/Responses

NHC Forecasts of Hurricane IKE (2008)



Forecasts of Hurricane IKE with the GMM



TC 01A (5/6) and Kesiny (5/2)

Init at 00Z May 1 2002

TC 02B(5/9) and Errol (5/10)

Init at 00Z May 6 2002

Super-Typhoon Hagibis (5/15)

Init at 00Z May 11 2002

Hurricane Alma (5/25)

Init at 00Z May 22 2002