Scale Interactions of Tropical Waves and Tropical Cyclone Formation in a Global Mesoscale Model

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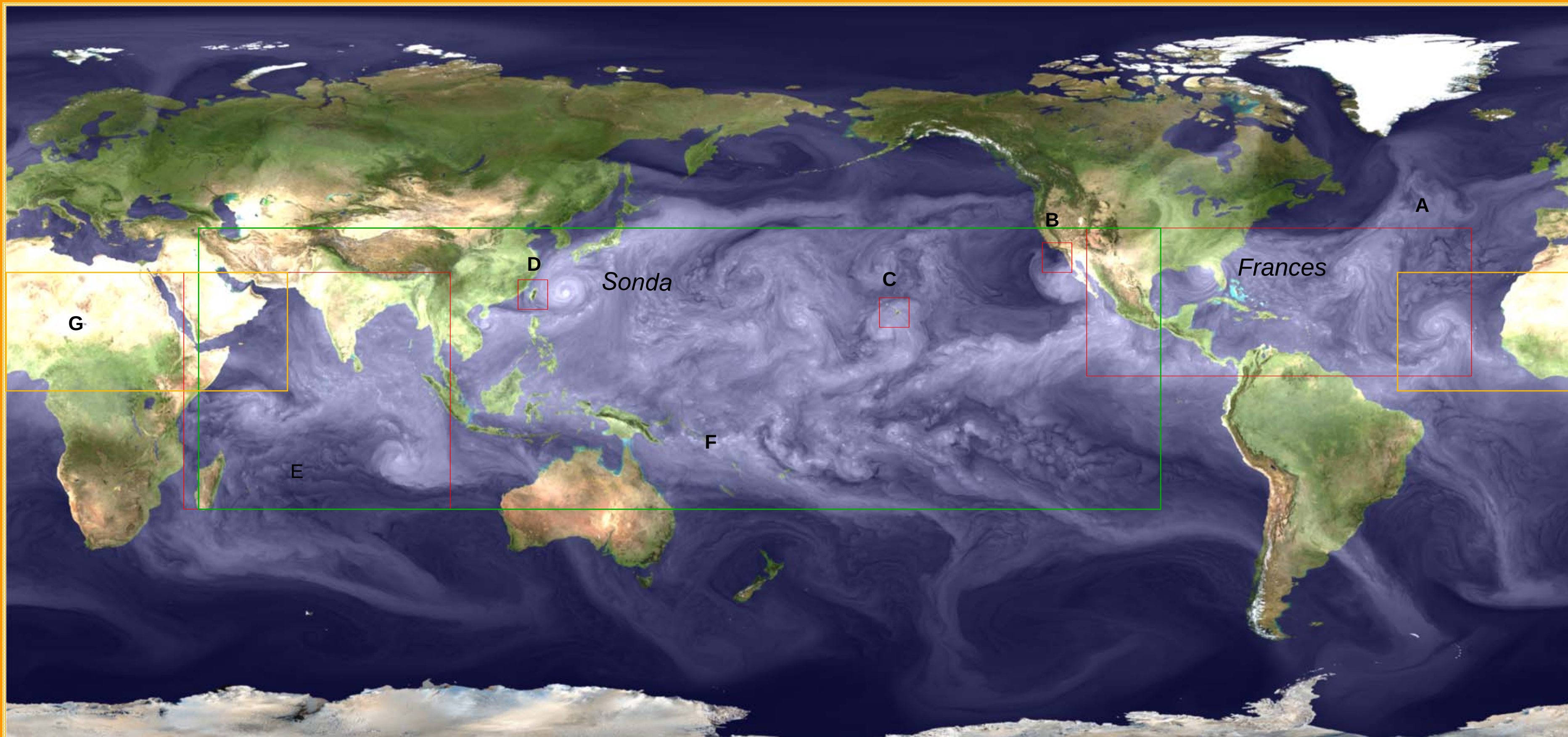

5-day forecasts of total precipitable water
initialized at 0000 UTC 1 September, 2004 with the 1/12º fvGCM

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

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Introduction

Over the past several decades, tropical cyclone (TC) track forecasts have been steadily improving, but intensity and genesis forecasts have lagged behind. One of the major challenges in TC genesis prediction is the accurate simulation of complex interactions across a wide range of scales, from the large-scale environment (deterministic), to mesoscale flows, down to convective-scale motions (stochastic). General circulation models (GCMs) have been used to study TC genesis statistics and inter-annual variability, but their insufficient grid spacing and poor physics parameterizations are known limiting factors. Recent advances in high-resolution global modeling and supercomputing have made it possible to mitigate some of the aforementioned issues. One of the important questions to be answered is: if and how the lead time for predicted TC formation can be extended?

In a series of recent papers by Shen et al. (2010a,b,c; 2011), we have shown that accurate simulations of multiscale interactions associated with large-scale tropical waves can achieve the above goal, including

- sophisticated multiscale interactions during the formation of Nargis (2008) associated with an equatorial Rossby wave in 7-day simulations;
- simulations of twin tropical cyclones associated with a large-scale tropical system Madden-Julian Oscillation and mixed Rossby gravity wave;
- remarkable simulations for the formation of multiple African Easterly waves and their association with hurricane formation (e.g., Helene, 2006) in 30-day experiments.

In this article, a brief summary on the aforementioned studies will be given.

Project Goal:
A Scenario in Decadal Survey Missions

Among the scenarios in the Decadal Survey Missions (DSM) report recommended by National Research Council (NRC) in 2007 (Table 1), "*Extreme Event Warning"* is one of the top priority scenarios. It focuses on *"discovering predictive relationships between meteorological and climatological events and less obvious precursor conditions from massive data sets."* Thus, in this project, the predictive relationship between the large-scale tropical wave and TC formation is examined with the global mesoscale model (slide 3) and supercomputing and visualization technology at NASA (slide 4). The architect of the <u>C</u>oupled <u>A</u>dvanced <u>M</u>ultiscale modeling and concurrent <u>Vis</u>ualization system (CAMVis) is shown in slide 6.

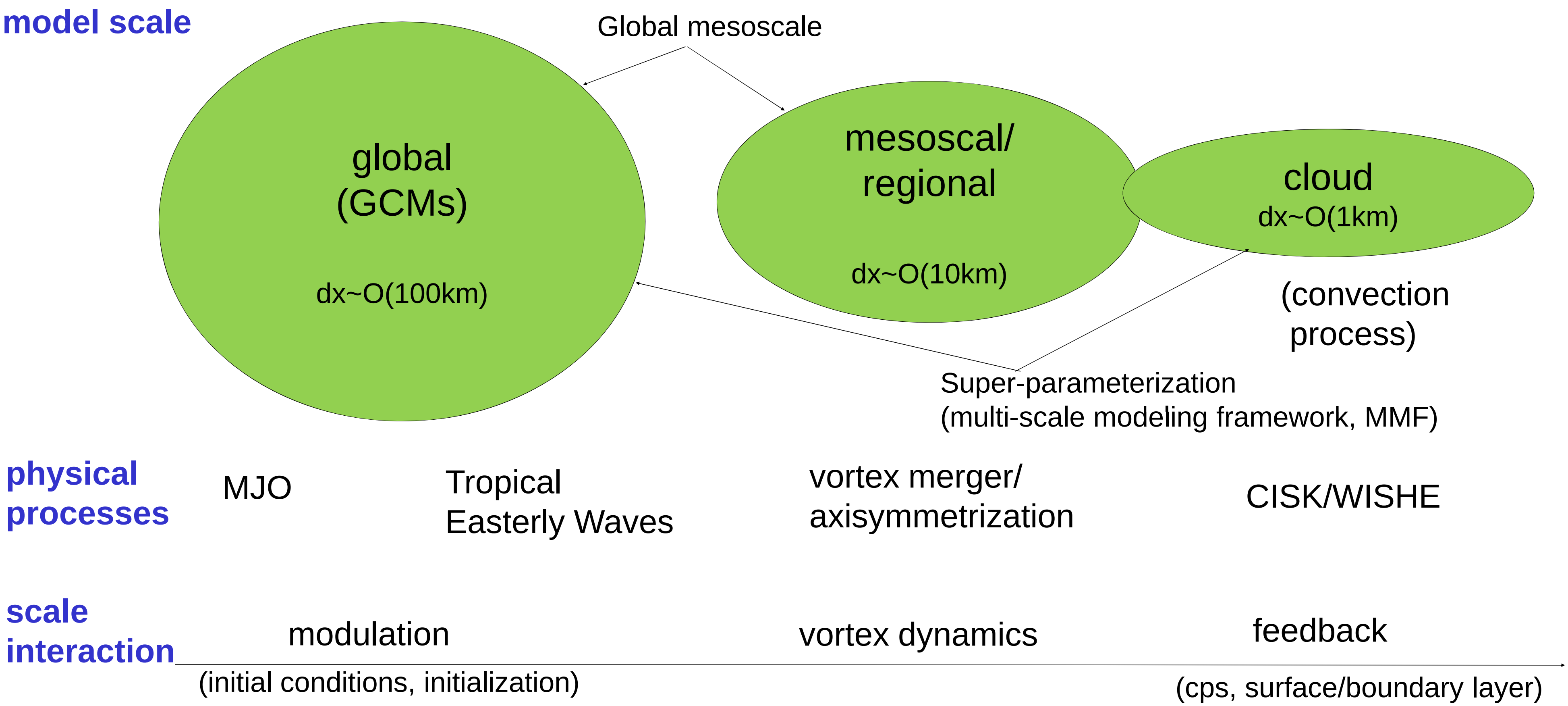
Table 1: Highlights of Decadal Survey Missions

- **Aerosol -Cloud-Ecosystems Mission (<u>ACE</u>, 2010-2013):** *to reduce uncertainty about climate forcing in aerosol-cloud interactions*
- **Extended <u>Ocean Vector Winds</u> Mission (XOVWM, 2013-2016):** *to further improve <u>hurricane forecasts</u>* and warnings *(suggested by previous studies with QuikSCAT winds)*
- **ICES at-II Mission (2010-2013):** *to address the contribution of changing terrestrial ice cover to global sea level; thus, to project the effects of <u>sea-level change</u> on growing populations and infrastructure along almost all coastal regions*
- **Precipitation and All-weather Temperature and Humidity (<u>PATH</u>) Mission (2016-2020):** *to provide early identification and reliable <u>forecasting of the track and intensity</u> of tropical cyclones with observations of three-dimensional atmospheric temperature and water vapor, as well as sea surface temperature and precipitation fields under all weather conditions*
- **Soil Moisture Active-Passive Mission (<u>SMAP</u>, 2010-2013):** *to improve <u>flood forecasts</u> and thus improve the capability to protect downstream resources through assimilation of satellite-derived soil moisture that is a key control on evaporation and transpiration at the land atmosphere boundary*
- **3D Tropospheric Winds from Space-based Lidar MISSION (<u>3D-Winds</u>, 2016-2020):** *to provide more accurate, more reliable, and <u>longer-term weather forecasts</u>, which are driven by fundamentally improved tropospheric wind observations from space.*

National Research Council (NRC) Decadal Survey, 2007: *Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond. The National Academies Press,* Washington, D.C.

Multiscale Modeling Approach

To improve the prediction of TC's formation, movement and intensification, we need to improve the model to accurately simulate interactions across a wide range of scales, from the large-scale environment (deterministic), to mesoscale flows, down to convective-scale motions (stochastic).



CISK: conditional instability of second kind; **CPs:** cumulus parameterizations; **MMF:** multiscale modeling framework; **MJO:** Madden-Julian Oscillation; **TC:** Tropical Cyclone; **WISHE:** Wind induced surface heat exchange;

NASA Supercomputing and Visualization Systems

Pleiades Supercomputer (ranked 3rd in late 2008; 6th in June, 2010)

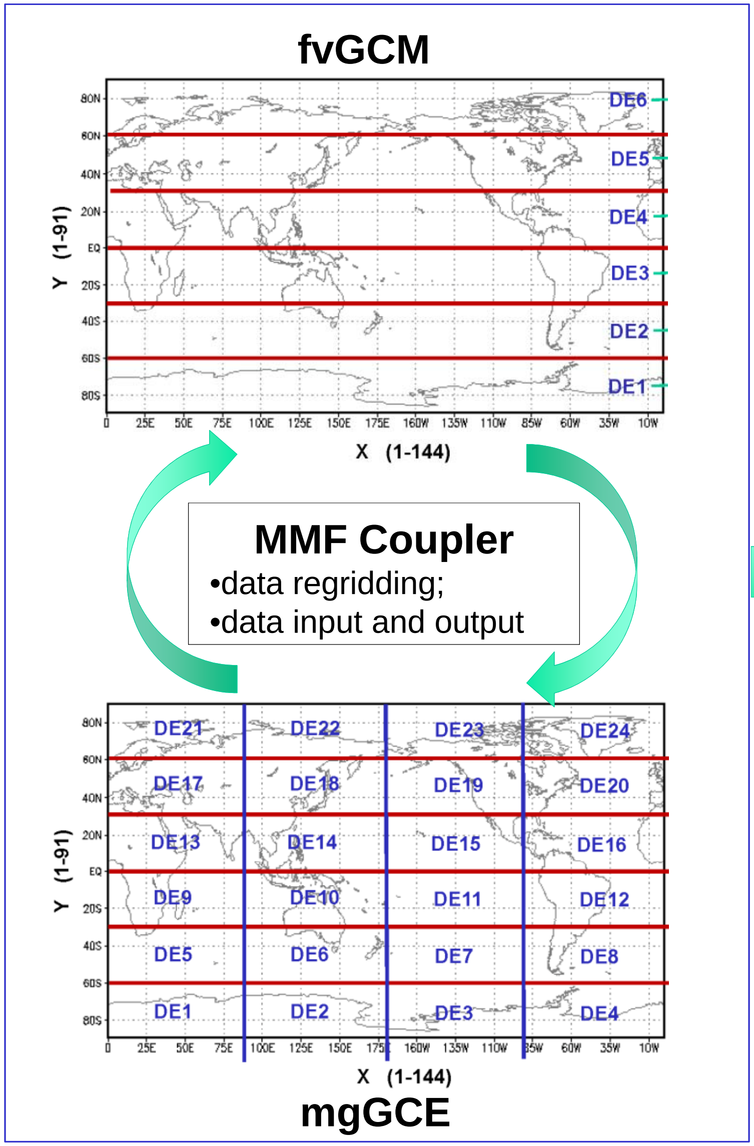
- R_{max} of 773 teraflops (LINPACK); R_{peak} of 973.29 teraflops
- 144 Cabinets with 64 nodes/cabinet
- 81,920 cores in total; Xeon 5472 (Harpertown), Xeon 5570 (Nehalem), Xeon 5670 (Westmere)
- 127 TB memory
- 3.1 PB disk space
- Largest InfiniBand network: 9,216 nodes; Partial 11D hypercube; Direct visualization cluster connections

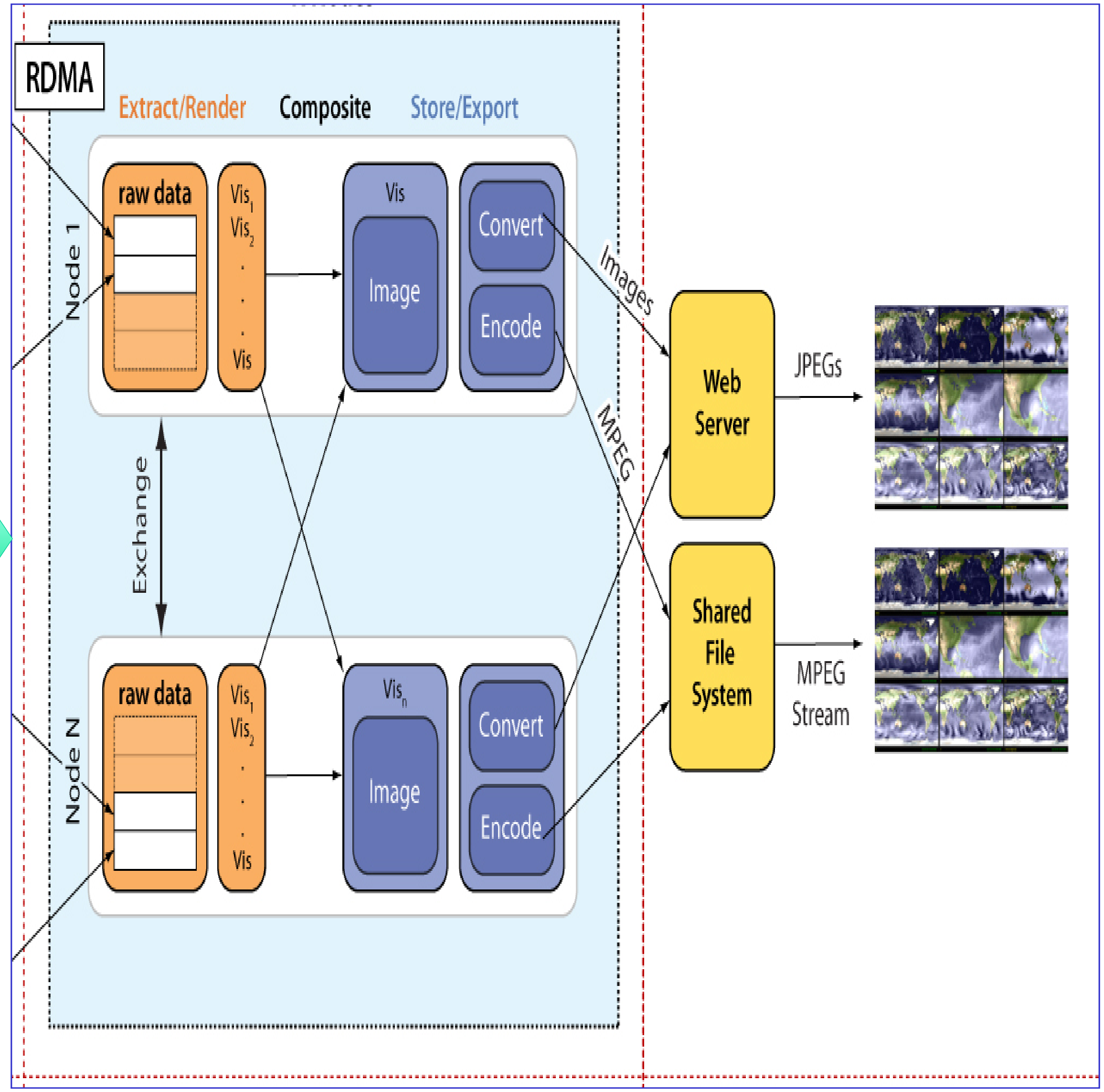
- Supercomputer-scale visualization system
  - 8x16 LCD tiled panel display
  - 245 million pixels
- 128 nodes
  - Dual-socket quad-core Opterons
  - 1024 cores, 128 GPUs
- InfiniBand (IB) interconnect to Pleiades
  - 2D torus topology, 32 links to Pleiades
  - 9x2 switches
  - High-bandwidth concurrent visualization

Architecture of the CAMVis v1.0

(the **C**oupled **A**dvanced **M**ultiscale modeling and concurrent **Vis**ualization systems)

Multi-scale Modeling with "M" nodes | **Current Visualization with "N" nodes** | **Real-time Display**





Simulation | **Extraction** | **Visualization** | **MPEG generation**

Nargis (2008) and an Equatorial Rossby Wave

Very severe cyclonic storm Nargis devastated Burma (Myanmar) in May 2008, caused tremendous damage (~$10 billion) and numerous fatalities (~130,000 deaths), and became one of the 10 deadliest tropical cyclones (TCs) of all time. To increase the warning time in order to save lives and reduce economic damage, it is important to extend the lead time in the prediction of TCs like Nargis. Seven-day high-resolution global simulations with real data show that the initial formation and intensity variations of TC Nargis can be realistically predicted up to 5 days in advance (bottom). Preliminary analysis (slide 7) suggests that improved representations of the following environmental conditions and their hierarchical multiscale interactions were the key to achieving this lead time: (1) a westerly wind burst and equatorial trough, (2) an enhanced monsoon circulation with a zero wind shear line, (3) good upper-level outflow with anti-cyclonic wind shear between 200 and 850 hPa, and (4) low-level moisture convergence.

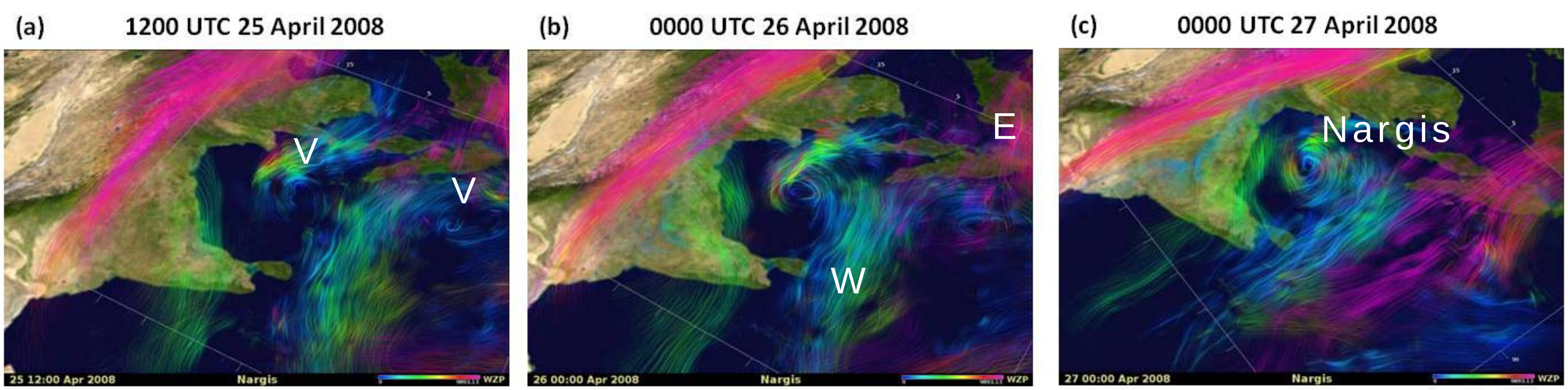
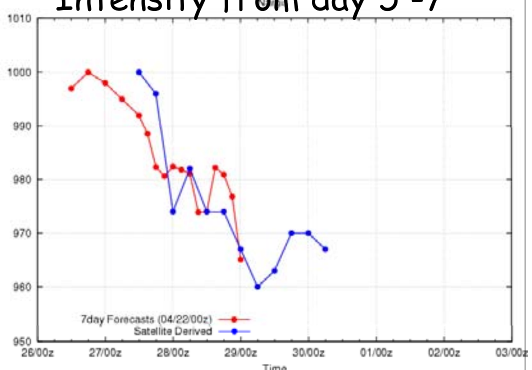


Figure: Realistic 7-day simulations of the formation and initial intensification of TC Nargis (2008) initialized at 0000 UTC April 22, 2008, showing streamlines at different levels. Low-level winds are in blue and upper-level winds in red: (a) formation of a pair of low-level mesoscale vortices (labeled in 'V') at 84h simulation, which are associated with an equatorial Rossby wave; (b) intensification of the northern vortex (to the left); (c) formation of TC Nargis associated with the enhancement of the northern vortex. Approaching easterly upper-level winds (labeled in 'E') increase the vertical wind shear, suppressing the enhancement of the southern vortex (to the right) in panel (b).

Hierarchical Multiscale interactions of Nargis (2008)

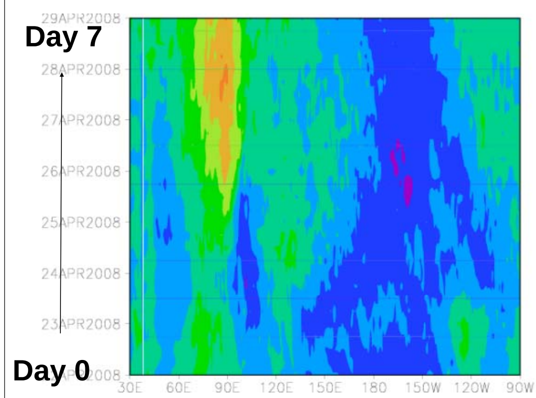
7-day global multiscale simulations suggest the following favorite factors for the formation and initial intensification of tropical cyclone Nargis:

Intensity from day 5 -7



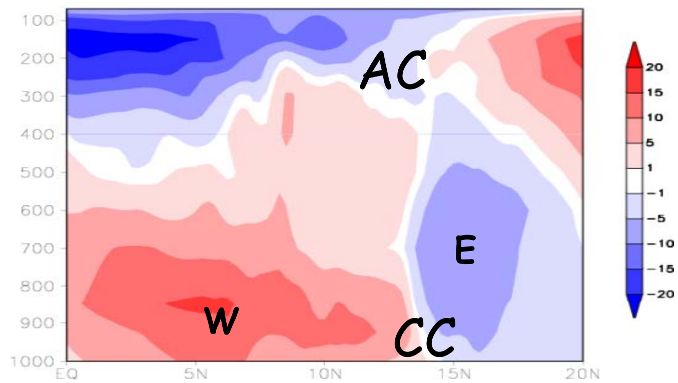
Time evolution of simulated min SLP (red) from day 5 to day 7, as compared to the satellite observation (blue).

Northward movement of WWB



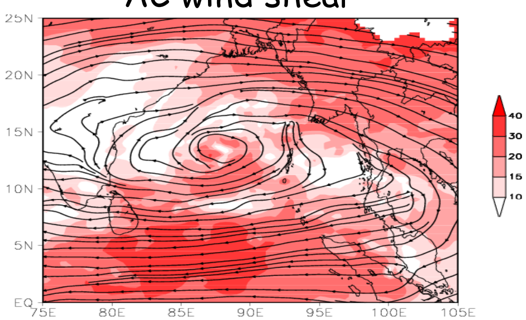
Time/longitude diagram of zonal winds averaged over latitude 5ºN to 10ºN. West Wind Belt/Burst (WWB) is indicated by orange area. (Northward movement is clearly shown as the above is compared to the one averaged latitude 5Sº to the equator.)

Enhanced Monsoonal circulation



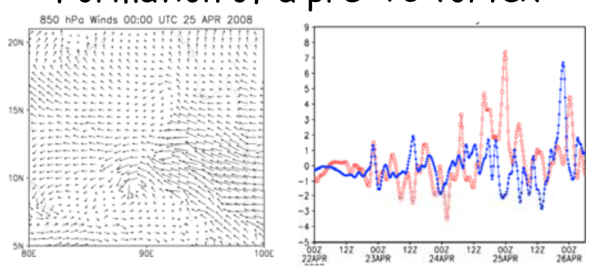
Altitude/latitude cross section of zonal winds averaged over longitude 80ºE-90ºE. Westerly and early winds are shown in red and blue. Weak vertical wind shear is indicated by the "vertical orientation of the white line". Middle- and low-level cyclonic circulation (CC) and upper-level anti-cyclonic circulation (AC) become superimposed at 132h simulation.

AC wind shear



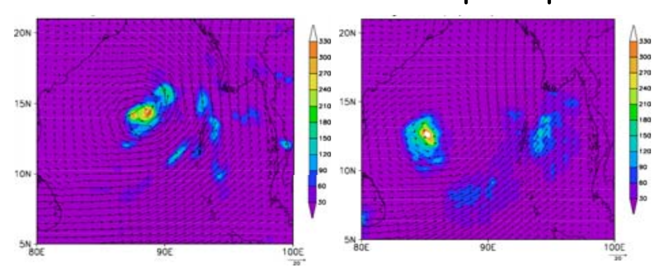
126h simulation of vertical wind shear between 850- and 200-hap, showing anti-cyclonic wind shear and good upper-level outflow.

Formation of a pre-TC vortex



72h simulation of 850-hpa winds (left) and time evolution of low-level convergence (right), showing the formation of a pre-TC vortex associated with peaks of low-level convergence

Vortex circulation and precip

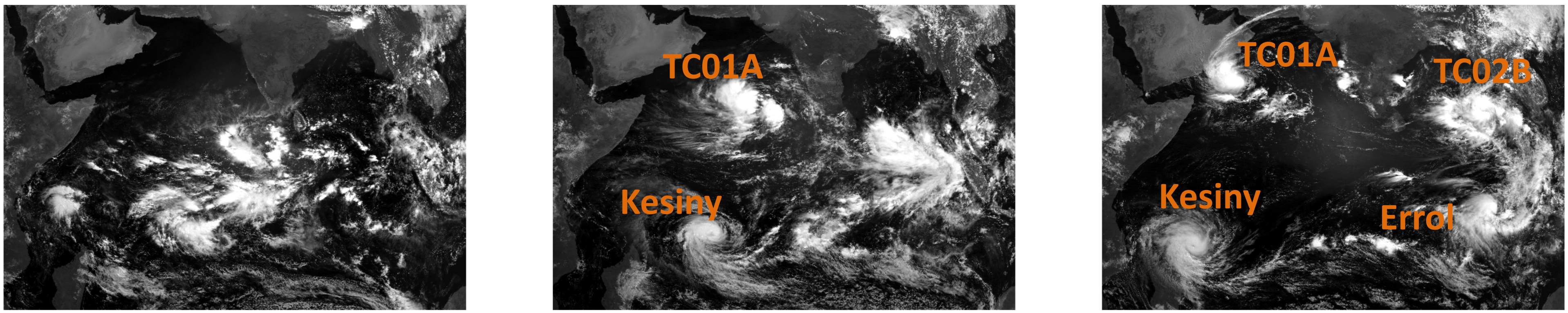


Averaged precip and 850-hPa winds from day 5 to day 7 (left) and averaged NASA TRMM precip and NCEP Reanalysis winds (right)

Twin Tropical Cyclones and an MJO in May 2002

Previous studies suggest that twin tropical cyclones (TCs), symmetric with respect to the equator, may occur associated with a large-scale Madden-Julian Oscillation (MJO). Here, it is shown that high-resolution simulations of twin TCs associated with the MJO in 2002 are in good agreement with the satellite observations. Multiscale Interactions between a mixed Rossby gravity wave and the twin TC are shown in slide 9.

0630 UTC 1 May 2002 | 0000 UTC 6 May 2002 | 0000 UTC 9 May 2002



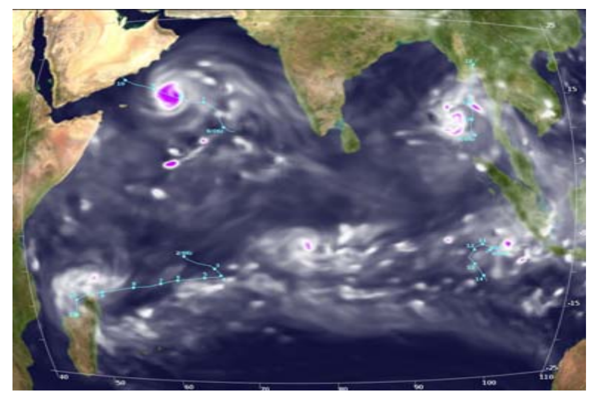
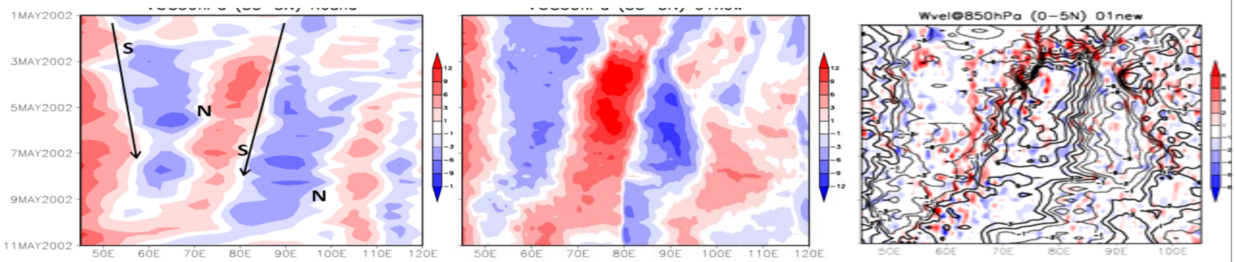


Figure: Predictions regarding the formation of twin tropical cyclones in the Indian Ocean: (a) MJO-organized convection over the Indian Ocean at 0630 UTC 1 May 2002. When the MJO moved eastward, two pairs of twin TCs appeared sequentially on 6 May (b) and 9 May (c), including TC 01A, Kesiny, TC 02B and Errol. Two TCs (01A and 02B) with anti-clockwise circulation appeared in the Northern Hemisphere, while the other two TCs (Kesiny and Errol) with clockwise circulation in the Southern Hemisphere; (d) Four-day forecasts of total precipitable water, showing realistic simulations of TC's formation and movement (see Shen et al., 2010c and 2011 for details).

<u>Shen, B.-W., W.-K. Tao</u>, et al. 2011: Forecasting Tropical Cyclogenesis with a Global Mesoscale Model: Preliminary Results for Twin Tropical Cyclones in May 2002. (to be submitted)

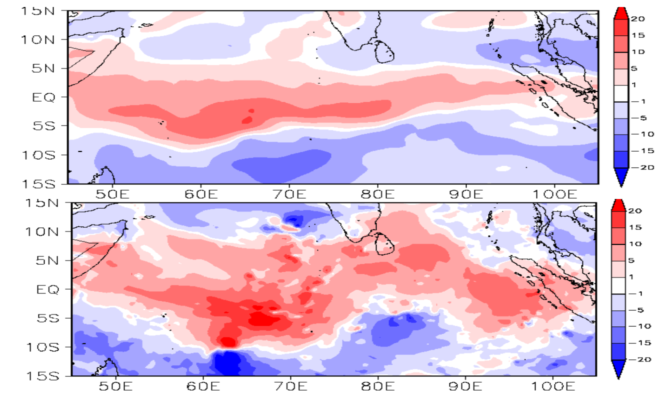
Interactions of Twin TCs and MRG wave

Wavelength reduction of mixed Rossby gravity (MRG) wave



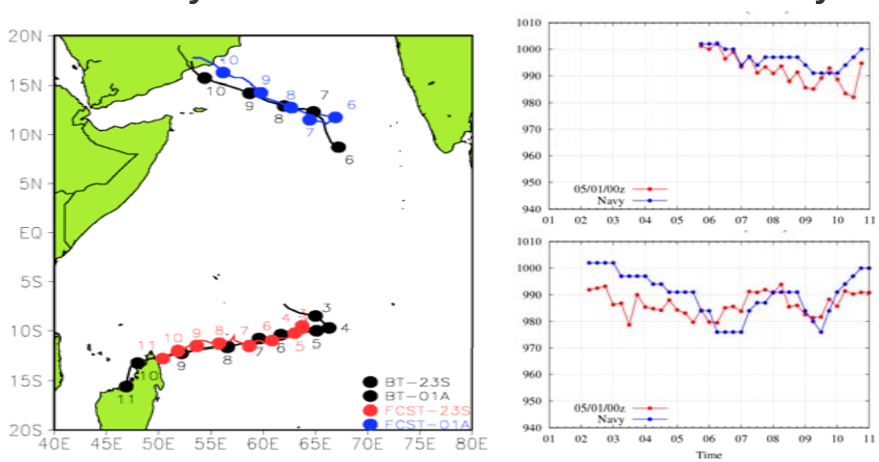
Time/longitude diagram of meridian winds from NCEP analyses (a) and the 10-day control run initialized at 00Z 1 May 2002 (b). Northerly (southerly) winds are indicated in red (blue). The westward-propagating disturbances with the sloping northerly to southerly flow couplets that are nearly asymmetric about the equator are likely associated with an MRG wave.(c) Time/longitude diagram of 850mb vertical velocity (shaded) and meridian winds (contour).

MRG Wave Development



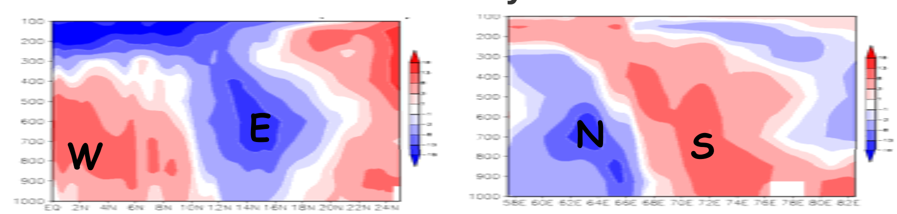
Simulations of 850-hPa zonal winds at the initial time and the integration of 96 hours.

10-day Fcst of Twin TCs' Track and Intensity



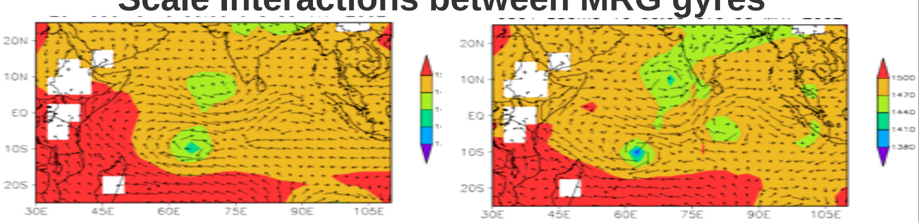
Track (a) and Intensity simulations of TCs 01A (b) and 23S (c) from the 10-day run initialized at 00Z 1 May 2002, as compared to the observations. The first record for TC 23S (01A) was issued at 06Z 3May (18Z 5 May).

Evolution of Low-level Cyclonic Circulation



120h simulations of zonal (left) and meridian winds (right)

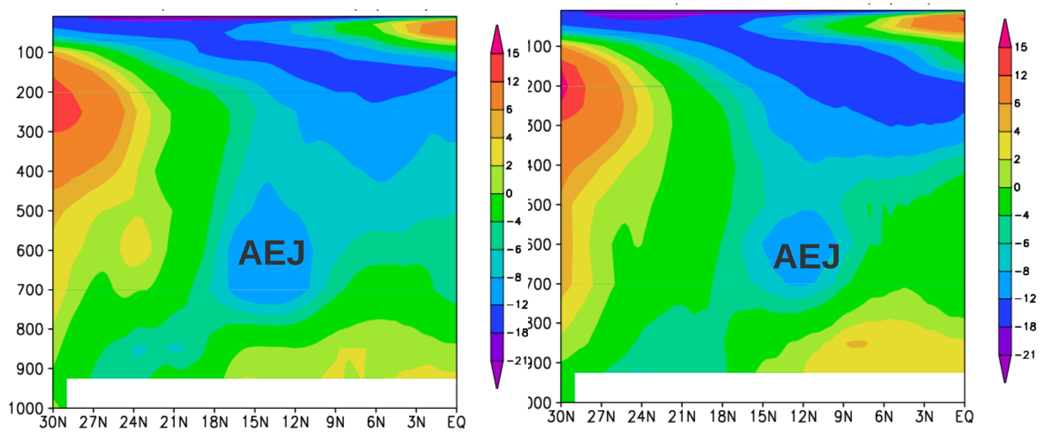
Scale Interactions between MRG gyres



850-hPa winds (vectors) and geopotential heights (shaded) at 00Z 5 May 2002 from NCEP analyses (left) and the control run (right).

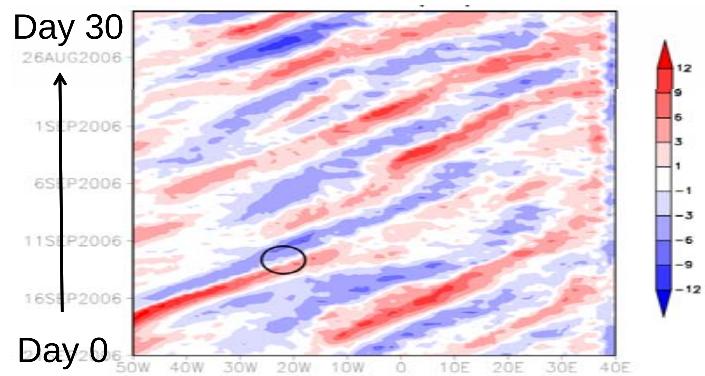
Multiscale Interactions of AEJ, AEWs, Hurricane and Surface Processes in a 30-day run

Analysis and Simulation of African Easterly Jet (AEJ)



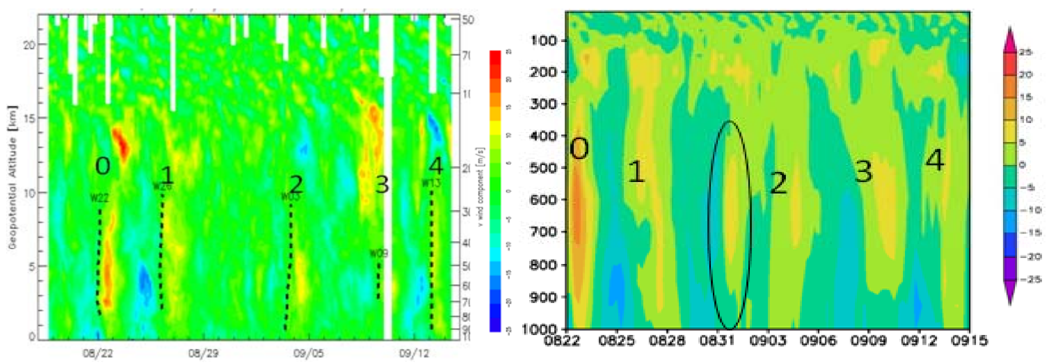
A 30-day averaged African Easterly Jet (AEJ) along longitude 20^{o}E from GFS analysis (left) and a 30-day simulation (right) initialized at 0000 UTC August 22, 2006

African Easterly Waves (AEWs)



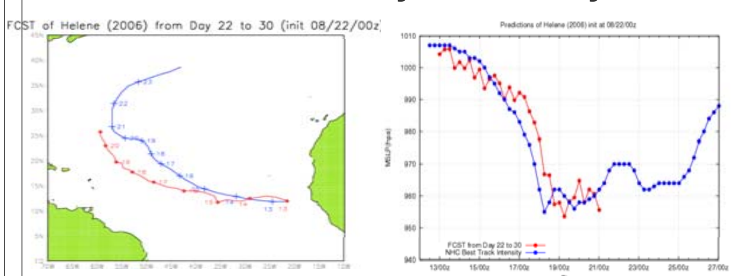
Six African Easterly Waves (AEWs) in a 30-day simulation . The black circle roughly indicates the timing and location of Helene's formation.

Detection of Multiple AEWs



Time-altitude cross sections of meridional winds at (23.5^{o}W, 14.9^{o}N) from NAMMA (NASA African Monsoon Multidisciplinary Analyses) observations (left) and model simulation (right).

Track and Intensity in a 30-day run



Track (left) and intensity (right) forecasts for Hurricane Helene from Day 22 to 30. Red and blue lines indicate model predictions and best track, respectively.

15-day Simulations of an MJO in May 2002

Accurate prediction of tropical activity at sub-seasonal scales is crucial for extending numerical weather prediction beyond 2 weeks. Among the challenges of this goal is accurate forecasting of a Madden-Julian Oscillation (MJO). This figure is to show that both the fvGCM and fvMMF can realistically simulate the MJO up to 15 days.

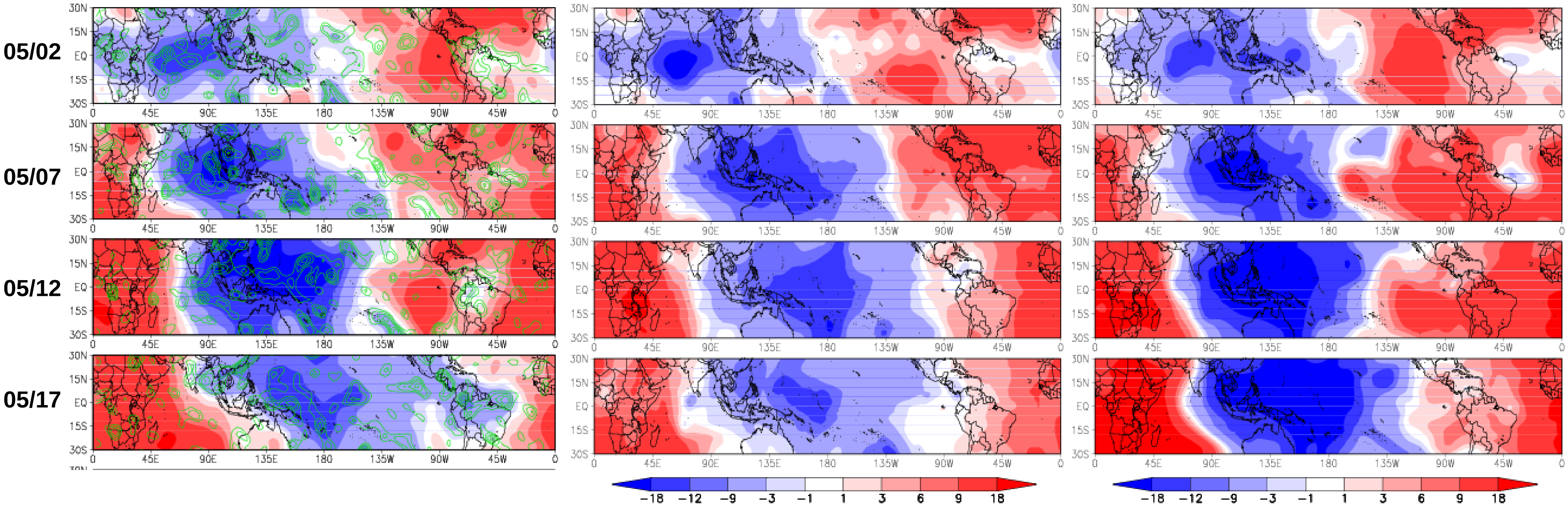


Figure: Velocity potential at 200 hPa every 5 days in May 2002 from NCEP analysis (left panels), 15-day fvGCM model predictions at 1/8 degree resolution (middle panels), and 15-day fvMMF model predictions (right panel). The velocity potential plots showe the observed and predicted patterns and propagations of Madden-Julian Oscillation (MJO). The high-resolution fvGCM is able to reproduce realistically the observed patters and intensity as NCEP analysis. The fvMMF even with coarse-resolution (2x 2.5 degree) is also able to predict the large-scale MJO event, except its intensity is somewhat overestimated .

Conclusion: mesoscale predictability

To extend the lead time of TC prediction, we investigate the multiscale interactions of tropical waves and TC formation, including: (a) very severe cyclonic storm Nargis (2008) and its association with an Equatorial Rossby wave; (b) twin TCs in May 2002 and their association with a mixed Rossby gravity wave; and (c) Hurricane Helene (2006) and its association with an AEW. It is found that TC formation can be realistically with a lead time of 5 days and 3~5 days in cases (a) and (b), respectively. Of interest is the potential to extend the lead time for predicting the formation of Helene (e.g., a lead time of up to 22 days) as the 4th AEW is realistically simulated. Detailed discussions can be found in slides 13 and 14.

Nearly 25 years ago, Dr. Anthes and his colleagues conducted a series of predictability studies with a mesoscale model, and suggested that

- *the development of mesoscale weather systems may be classified as occurring through one or both of two mechanisms: (ii) forcing on the mesoscale from inhomogeneities at the earth's surface and (ii) internal modifications of large-scale flow patterns that lead to smaller-scale circulations.*

He then made the following hypotheses on the mesoscale predictability:

- *an accurate specification of large-scale thermodynamic and momentum fields, together with realistic physical forcing at the surface, adequate representation of diabatic effects in the free atmosphere, and the appropriate resolution, may be sufficient to predict the evolution of some mesoscale systems for hours or even a few days in advance of their development; and*
- *when there are no strong mesoscale circulations present initially, it may be unnecessary to observe and analyze mesoscale detail for the model's initial conditions.*

Our case studies enabled by the global mesoscale model and supercomputing technology seem to support the above hypotheses by Dr. Anthes. However, much work is still required to assure the model's consistent performance. In addition, as the mesoscale predictability (of TCs) is dependent of the representation of the large-scale flows, we will examine the extended-range (~15-30 days) simulations of large-scale flows such as AEWs and MJOs (e.g., slide 11) in order to extend the lead time of TC predictions.

Multiscale Interactions (in the Twin TC case)

1. 10-day experiments initialized at 00Z 1 May 2002 suggest that a mixed Rossby gravity (MRG) wave with baroclinicity appeared initially as the integral of three gyres (S_1, N_1 and S_2 in slide 9), all moving westward;
2. The MRG wave intensified in association with its wavelength reduction which is clearly shown by the faster westward phase speed in gyre S_2 than S_1;
3. As time progresses, low- and middle-level cyclonic circulation (CC) continued to develop and became "coherent" vertically, providing a favorite condition for TC genesis with zero vertical wind shear line centered at the CC;
4. The 1/4 wavelength phase lag between the meridian winds and the vertical velocity appears at the middle levels (e.g., 500 hpa) but is distorted at the low-level levels (e.g., 850 hpa), which is consistent with the conclusion of Holton (1975) that in-phase of geopotential height and the boundary friction induced convergence might contribute to the cut-off of the gyre (e.g., gyre N_1) from the equator;
5. After TC Kensiny and 01A formed on May 3 and May 6 respectively, these two TCs moved at different speeds and gradually appeared as a twin TC, indicating the transition of a MRG wave into an equatorial Rossby wave.

Multiscale Interactions (in the AEW case)

1. 30-day experiments initialized 00Z 22 August 2006 show that the statistical characteristics of multiple AEWs (including initiation and propagation) are realistically simulated with larger errors in the 5^{th} and 6^{th} AEWs. Remarkable simulations of a mean African Easterly Jet (AEJ) are also obtained.
2. While land surface processes may contribute to the predictability of the AEJ and AEWs (as a boundary value problem), the initiation and detailed evolution of AEWs still depend on the accurate representation of dynamic and land surface initial conditions and their time-varying nonlinear interactions (as an initial value problem).
3. Of interest is the potential to extend the lead time for predicting hurricane formation (e.g., a lead time of up to 22 days) as the 4^{th} AEW is realistically simulated.
4. In the experiment with climate SSTs, differences appear in the 5^{th} and 6^{th} AEWs, implying that the effects of using climatological SSTs on the simulation of AEW initiation begin to occur after 15-20 days of integration.
5. The reduced height of Guinea highlands causes significant differences in the simulations of AEWs since Day 15. For example, the initiation of the 4^{th}, 5^{th} and 6^{th} AEWs are influenced by this change, and the downstream development of AEWs (e.g., the 2^{nd} and 4^{th} AEWs) becomes weaker.

ESTO
Earth Science Technology Office

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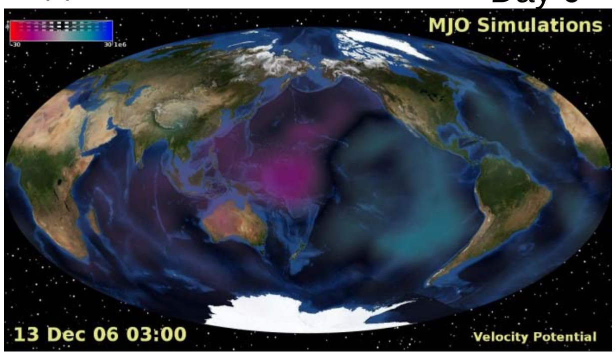
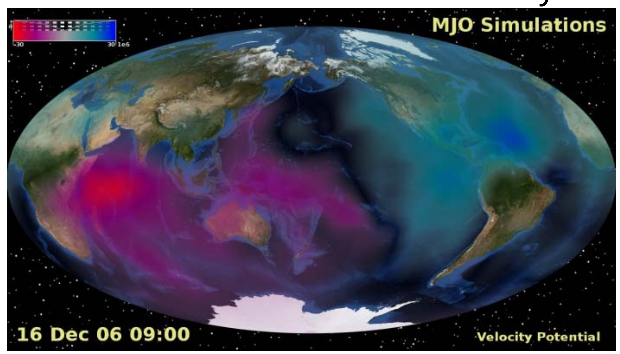
30-day Simulations of an MJO in Dec 2006

One of the most challenges in predicting an MJO is to simulating its life cycle, including initiation or formation, intensification, propagation, and weakening. This figure shows the life cycle of the MJO in December, 2006 is realistically simulated in a 30-day run with the model.

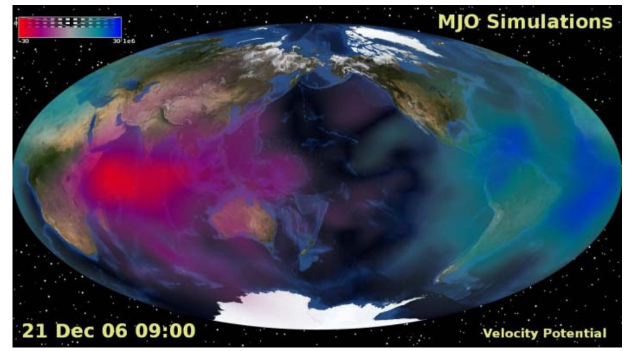
(a) Day 0



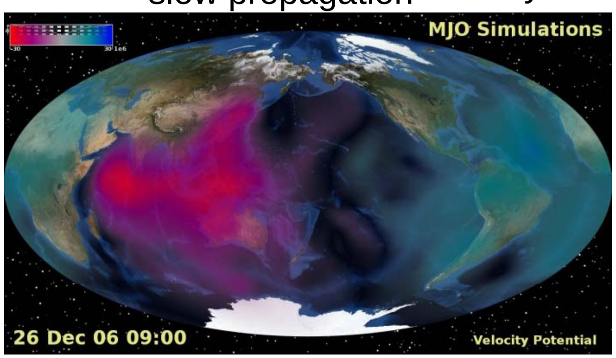
(b) initiation Day 3



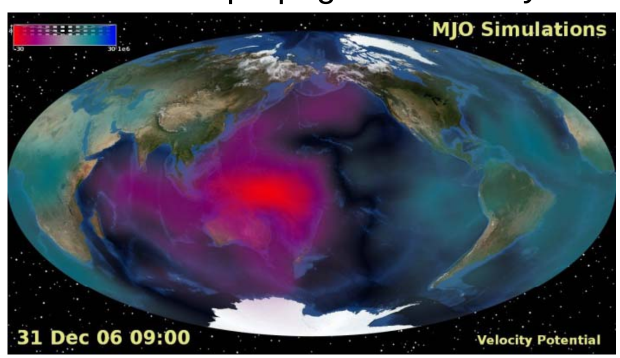
(c) intensification Day 8



(d) slow propagation Day 13



(e) fast propagation Day 18



(f) weakening Day 23

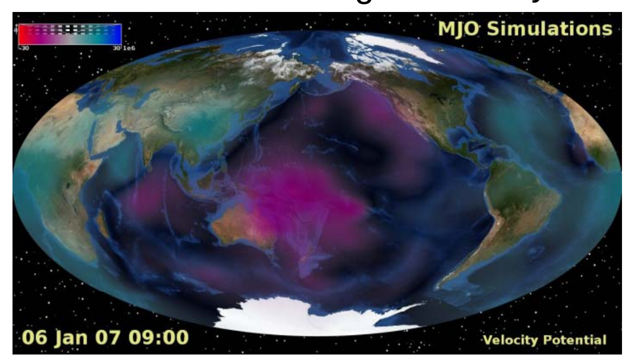


Figure: A 30-day simulation of an MJO initialized at 0000 UTC December 13, 2006, as shown in 200 hpa velocity potential. This simulation with the Goddard MMF (Tao et al., 2009) captures several major features usually associated with an MJO: (1) initiation of large-scale organized convection in the Indian 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.

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Anthes' Hypotheses on Mesoscale Predictability in 1980s

- *An easier problem, from the observational point of view, is the simulation of mesoscale phenomena which develop within large-scale, routinely observed circulations. The development of mesoscale weather systems may be classified as occurring through one or both of two mechanisms: (l) forcing on the mesoscale from inhomogeneities at the earth's surface and (2) internal modifications of large-scale flow patterns that lead to smaller-scale circulations.*
- *When there are no strong mesoscale circulations present initially, it may be unnecessary to observe and analyze mesoscale detail for the model's initial conditions.*
- *An accurate specification of large-scale thermodynamic and momentum fields, together with realistic physical forcing at the surface, adequate representation of diabatic effects in the free atmosphere, and the appropriate resolution, may be sufficient to predict the evolution of some mesoscale systems for hours or even a few days in advance of their development.*
- *In short, the key to accurate prediction of tropical cyclogenesis is the get the right large-scale fields, have sufficient resolution for TC spinup, and appropriate physics!*

References:

- *A note on <u>"Summary of Predictability Papers",</u>* by Dr. R. A. Anthes in July, 2009
- An email with the subject of *<u>"Some Earlier Work on Mesoscale Predictability"</u>* by Dr. R. A. Anthes in February, 2011