Recent Advances in Global Hurricane Modeling since Katrina

by

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Acknowledgements

NASA/GSFC: Wei-Kuo Tao, William K. Lau, Jiundar Chern,

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bios

Employment/Experiences:

- 2006 - Present: Research Scientist, ESSIC, University of Maryland
- 1999 - 2006: Research Scientist, Sr. Software Engineer, SAIC
- 1998 - 1999: PostDoc, NCSU
- 1995 - 1998: PhD student, Research/Teaching Assistant, NCSU
- 1994 - 1995: Research Assistant, NCU, Taiwan
- 1992 - 1994: Meteorological Officer (Unix System Application Developer and Administrator, military service), Weather Center of Weather Wing, Taiwan

Thesis and Dissertation :

(theoretical and modeling studies with a focus on comparisons among different scale weather systems from non-hydrostatic, hydrostatic, non-geostrophic, to quasi-geostrophic mountain waves.)

- Shen, B.- W., 1992: *A Linear Theory for a Three-Dimensional Flow over an Isolated Mountain*, Master Thesis, National Central University, Taiwan, (in Chinese) p. 85
- Shen, B.-W., 1998: *Inertia Critical Layers and Their Impacts on Nongeostrophic Baroclinic Instability.* North Carolina State University. 10/1998. p255. Advisor: Prof. Yuh-Lang Lin ←the lead author of the microphysics scheme (Lin et al., 1983)

Publications in 2010

Shen, B.-W., W.-K. Tao, W. K. Lau, R. Atlas**, 2010a:** Predicting Tropical Cyclogenesis with a Global Mesoscale Model: Hierarchical Multiscale Interactions During the Formation of Tropical Cyclone Nargis (2008) . J. Geophys. Res., 115, D14102, doi:10.1029/2009JD013140. (impact factor 3.082)
http://atmospheres.gsfc.nasa.gov/cloud_modeling/docs/Shen_2009JD013140.pdf

Shen, B.-W., W.-K. Tao, and M.-L. C. Wu, **2010b:** African Easterly Waves in 30-day High-resolution Global Simulations: A Case Study during the 2006 NAMMA Period. Geophys. Res. Lett., L18803, doi:10.1029/2010GL044355. (impact factor 3.204) http://atmospheres.gsfc.nasa.gov/cloud_modeling/docs/2010GL044355.pdf

Shen, B.-W., W.-K. Tao, and B. Green, **2010c:** Coupling NASA Advanced Multi-Scale Modeling and Concurrent Visualization Systems for Improving Predictions of Tropical High-Impact Weather (CAMVis). Submitted to Computing in Science and Engineering (accepted 9 November 2010) (impact factor 0.973)
http://atmospheres.gsfc.nasa.gov/cloud_modeling/docs/Shen_et_al_2010_CISE_Revised_Draft.pdf

Shen, B.-W., W.-K. Tao et al., **2010d:** Genesis of Twin Tropical Cyclones Revealed by a Global Mesoscale Model: the Role of Mixed Rossby Gravity Wave (to be submitted in December, 2010)

2010 Research Highlights

Bo-Wen Shen featured in the NASA News Story entitled "Supercomputer Reproduces a Cyclone's Birth, May Boost Forecasting"
http://www.nasa.gov/topics/earth/features/supercomputer-cyclone.html

Research results (Shen et al., 2010a,b,c) featured in the NASA news story for SC10 entitled "Getting to the Heart of the Storm"
http://www.nas.nasa.gov/SC10/Shen_HurricaneModeling_Backgrounder.html

Project demonstration was featured in NASA Press Release for SC10: "Supercomputing Conference Highlights NASA Earth, Space Missions" (selected as one of top 4 project demonstrations for SC10 among aeronautics, exploration, science, and space operations missions at NASA)
http://www.nasa.gov/home/hqnews/2010/nov/HQ_10-296_Supercomputer.html

Research (Shen et al., 2010a) listed one of four Research Breakthroughs by Univ. of Maryland at College Park in April 2010
http://www.umresearch.umd.edu/VPRPubfiles/103241-web.pdf

Outline

Introduction

Global Mesoscale Modeling with NASA Supercomputing Technology

Simulations of High-impact Tropical Weather
- Five AEWs and genesis of Hurricane Helene (2006) in 30-day runs

Summary and Conclusions

Scenarios in Decadal Survey

<u>Extreme Event Warnings</u> (near-term goal): *<u>Discovering predictive relationships</u> between meteorological and climatologic events and less obvious precursor conditions from massive data set* → multiscale interactions; modulations and feedbacks between large/long-term scale and small/short-term scale flows

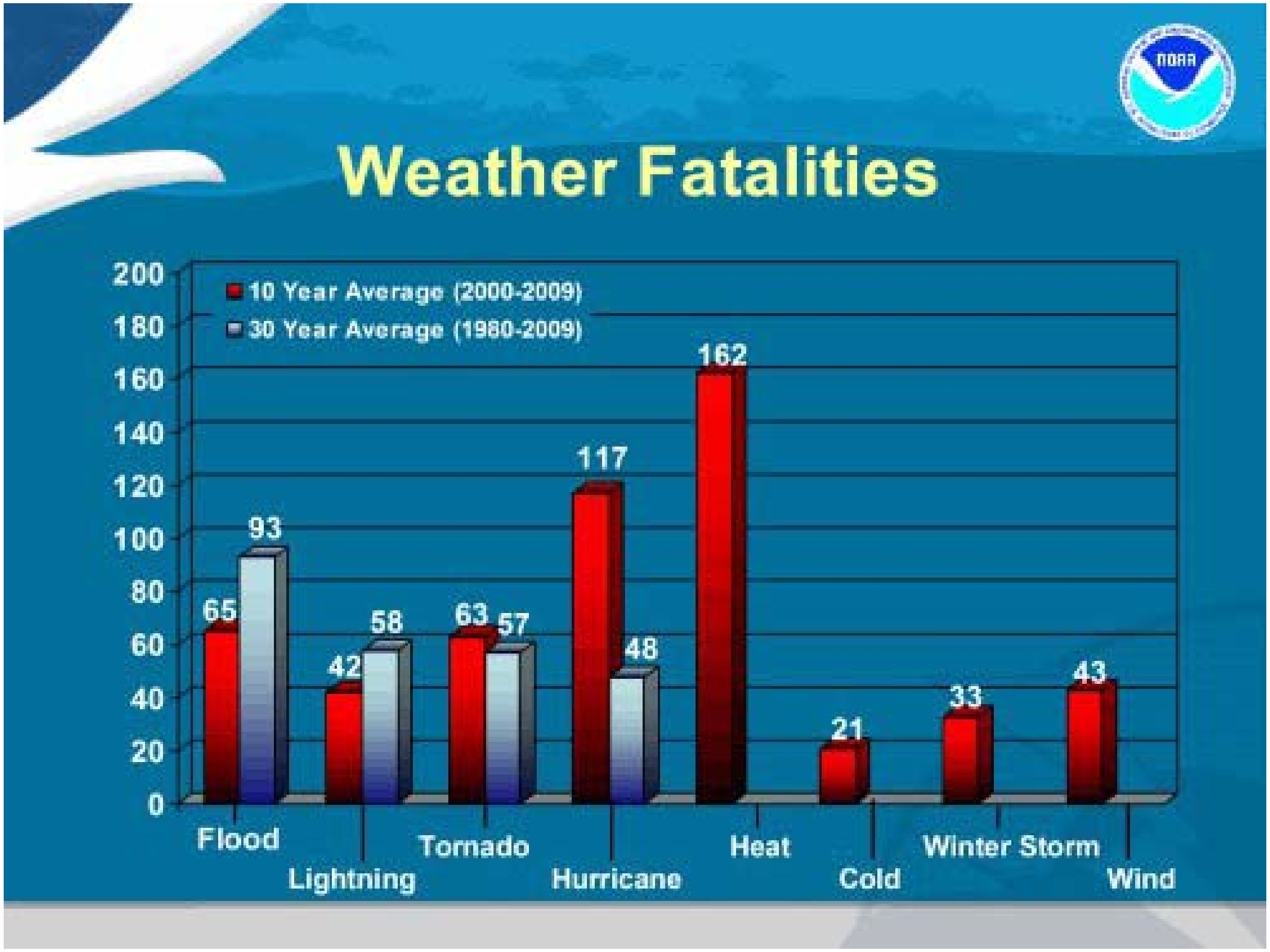
<u>Climate Prediction</u> (long-term goal): Robust estimates of primary climate forcings for improved climate forecasts, including local predictions of the effects of climate change. Data fusion will enhance exploitation of the complementary Earth Science data products to improve climate model predictions.

Courtesy of the Advanced Data Processing Group, ESTO PI WorkShop, Cocoa Beach, FL

National Research Council Decadal Survey, 2007

Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond. The National Academies Press, Washington, D.C. The decadal survey, which was completed at the request of NASA and other government agencies, recommends that: “The U.S. government, working in concert with the private sector, academe, the public, and its international partners, should renew its investment in Earth-observing systems and restore its leadership in Earth science and applications.”

The U.S. Natural Hazard Statistics



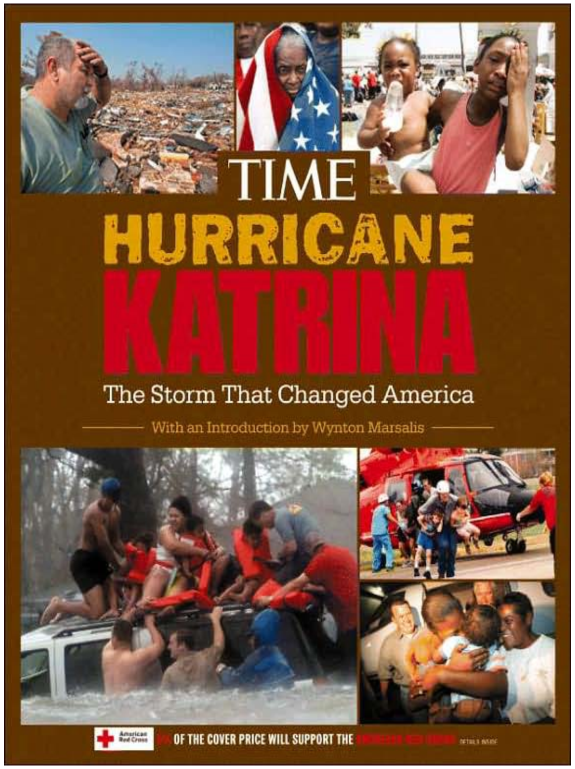
http://www.weather.gov/os/hazstats.shtml

High-impact Tropical Weather: Hurricanes

Each year tropical cyclones (TCs) cause tremendous economic losses and many fatalities throughout the world. Examples include Hurricane Katrina (2005), which is the costliest Atlantic hurricane in history, and TC Nargis, which is one of the 10 deadliest TCs of all time.

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! ($80 billion)
- http://en.wikipedia.org/wiki/Hurricane_Katrina



Severe Tropical Storm Nargis (2008)

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

Retired Hurricane Names

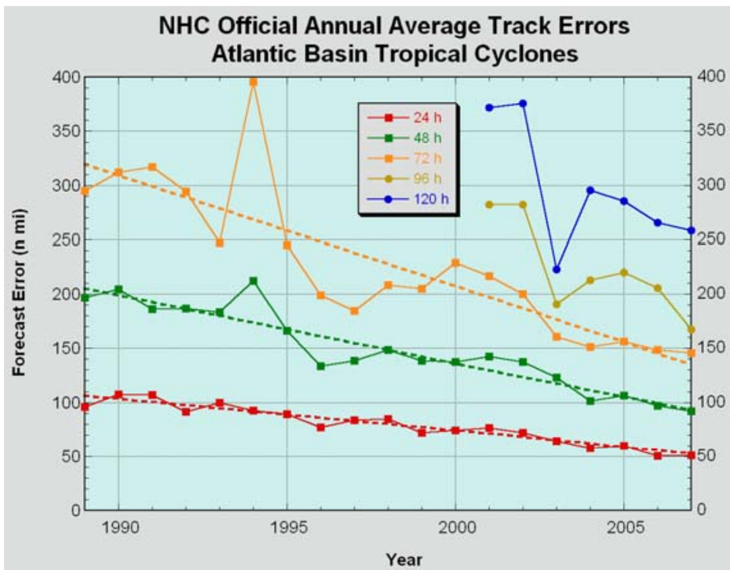
List of retired names by year

				1954 Carol Hazel	**1955** Connie Diane Ione Janet	**1956**	**1957** Audrey	**1958**	**1959**
1960 Donna	**1961** Carla Hattie	**1962**	**1963** Flora	**1964** Cleo Dora Hilda	**1965** Betsy	**1966** Inez	**1967** Beulah	**1968** Edna	**1969** Camille
1970 Celia	**1971**	**1972** Agnes	**1973**	**1974** Carmen Fifi	**1975** Eloise	**1976**	**1977** Anita	**1978**	**1979** David Frederic
1980 Allen	**1981**	**1982**	**1983** Alicia	**1984**	**1985** Elena Gloria	**1986**	**1987**	**1988** Gilbert Joan	**1989** Hugo
1990 Diana Klaus	**1991** Bob	**1992** Andrew	**1993**	**1994**	**1995** Luis Marilyn Opal Roxanne	**1996** Cesar Fran Hortense	**1997**	**1998** Georges Mitch	**1999** Floyd Lenny
2000 Keith	**2001** Allison Iris Michelle	**2002** Isidore Lili	**2003** Fabian Isabel Juan	**2004** Charley Frances Ivan Jeanne	**2005** Dennis Katrina Rita Stan Wilma	**2006**	**2007** Dean Felix Noel	**2008** Gustav Ike Paloma	**2009**

Progress of Hurricane Forecasts
(by National Hurricane Center)

Track Errors

better



Intensity Errors

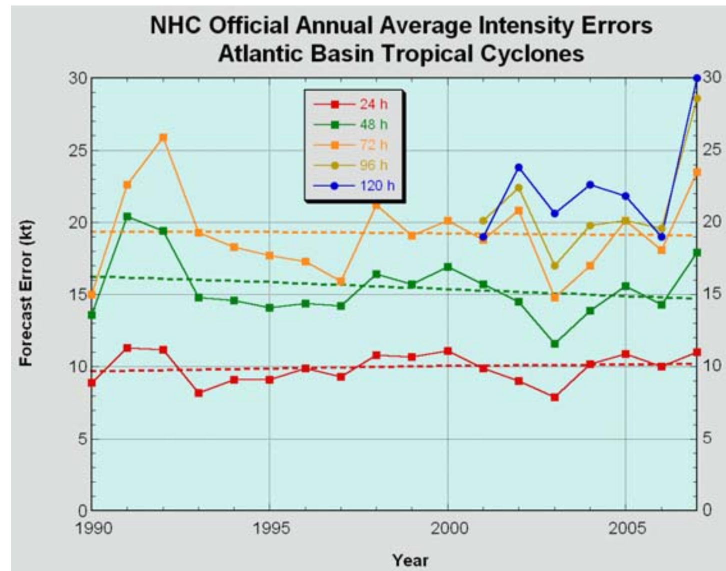
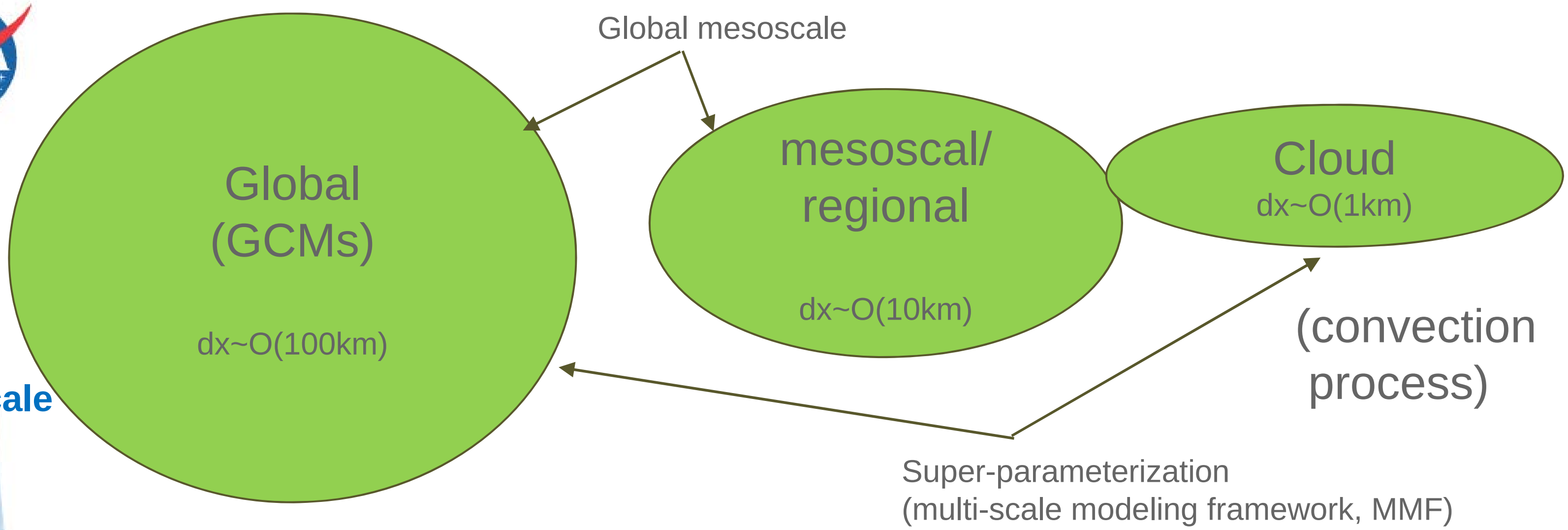


Figure: The progress of hurricane forecasts by National Hurricane Center. Horizontal axis indicates year, and vertical axis shows forecast errors. Lines with different color show different forecast intervals. *During the past twenty years, track forecasts have been steadily improving (left panel), but Intensity forecasts have lagged behind (right panel).*

Multiscale Interactions of TC Formation



Model scale

physical processes

MJO

Equatorial Rossby Wave; Mixed Rossby Gravity; Easterly wave

vortex merger/ axisymmetrization

CISK/WISHE

scale interaction

modulation

(initial conditions, initialization)

vortex dynamics

feedback

(cps, surface/boundary layer)

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;

Scientific Goals

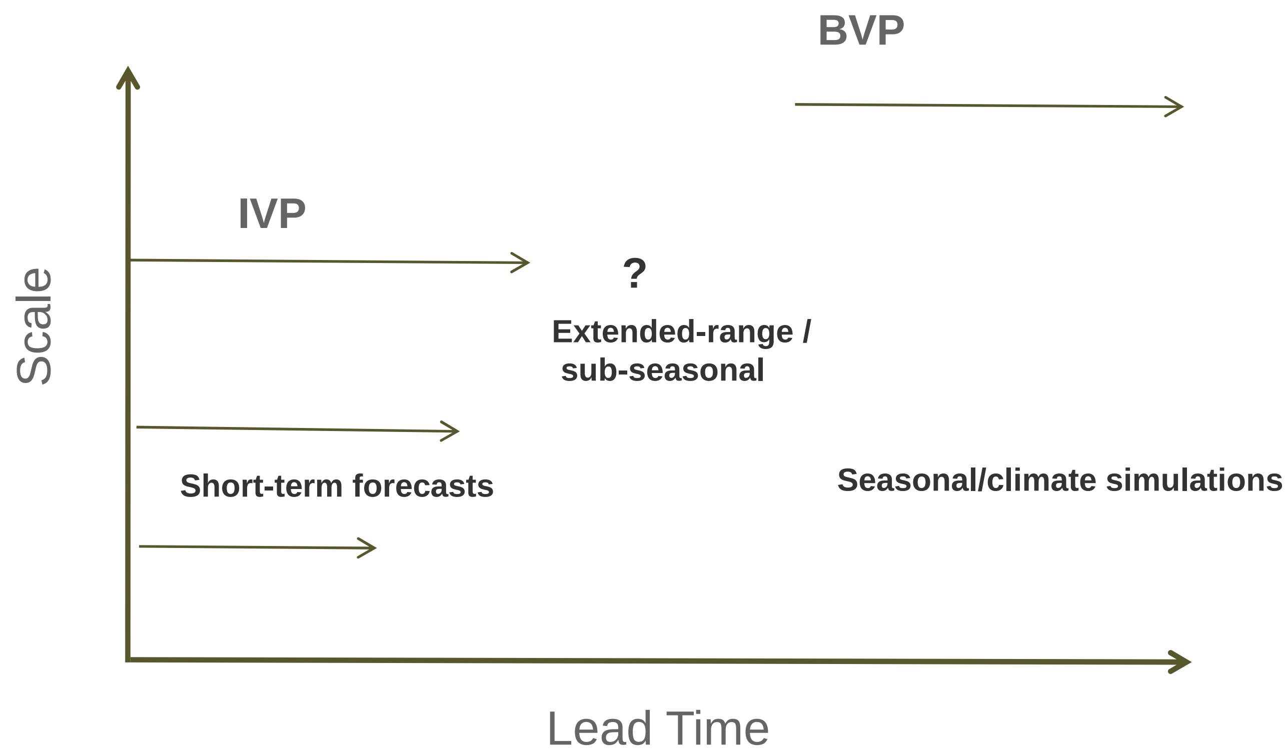
Accurate predictions of tropical cyclone(TC) activity at a large lead time can save lives and reduce economic costs.

To improve our understanding of mesoscale predictability for tropical cyclones (TCs) with the aim of extending the lead time of TC prediction and studying TC climate, experiments in the recent papers were performed to address the following questions:

(1) to what extent can large-scale flows determine the timing and location of TC genesis; Predictive relationship

(2) if and how realistically can a high-resolution global model depict those processes. Process studies

IVP vs. BVP



IVP: initial value problem
BVP: boundary value problem / forced problem

IVP vs. BVP

IVP:

$W'' + n^2 W = f_1(t,x)$

$W(t=0)=W_o(x)$

f_1: physics

BVP:

$W'' + n^2 W = f_1(t,x)$

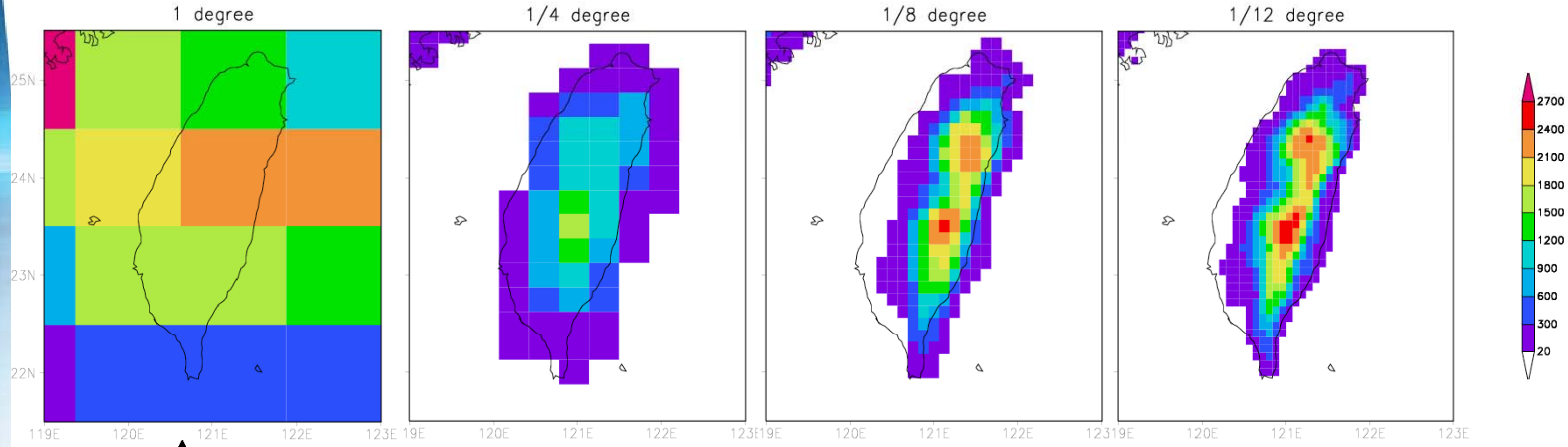
$W(x=0)=f_2(t,x)$

$W(x=L)=f_3$

eigenvalue, eigenmode

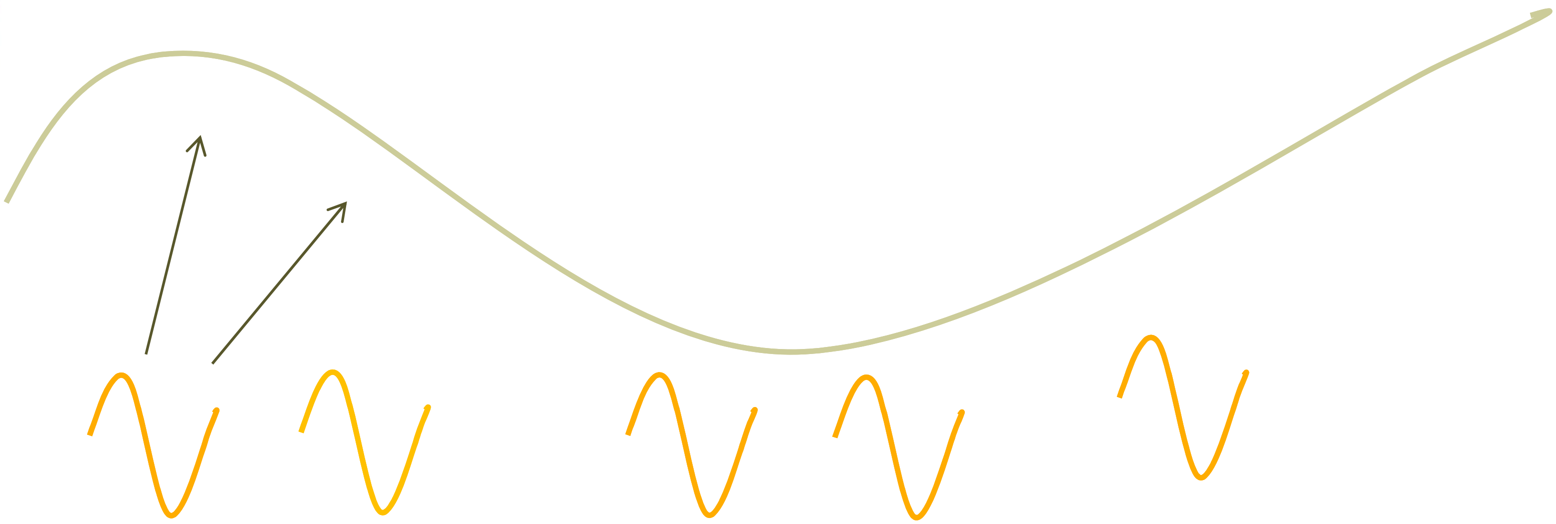
IVP: initial value problem
BVP: boundary value problem / forced problem

Terrains in a 4ºx4º box



Climate models:
feedbacks of terrain induced flows?

Scale Interactions



1. Is the initiation of small-scale weather system an IVP?
2. Is the initiation of any consecutive small-scale system an IVP? Does the initiation of the new system depend on the previous small-scale system or the large-scale (environmental) system?
3. If depending on the large-scale system, to what extent the previous small-scale system could impact/change the large-scale system? Phases (timing) and magnitudes (intensity). → what's impact scale in timing and spacing (on 2nd, 3rd, 4th small-scale system?) (similarly, does the resolved small-scale systems in the Ics have impact on the evolution of subsequent small-scale systems?)
4. From a modeling perspective, spin-up run time and initialization time are equally important.

Hierarchical Multiscale Interactions

Meaning:

- multiscale but “asymmetric” , e.g., large scale vs. small scale (e.g., organization vs. individuals)
- dependence of predictability at different scales (“P” may not be totally independent)
- (potential) existence of control-feedback-response relationship (at different stages) that can be simulated with numerical models (e.g., Q-E for CPs?)
- a different range of “involved” scales at a different stage of a (TC) lifecycle

Implications:

From a modeling perspective, clarifications of the following terms might be helpful to understand the hierarchical (two-way) multiscale interactions.

- **lifetime of the large-scale flow (forcing duration)**: the period that the large-scale flow could act as a forcing, (e.g., barotropic or baroclinic instatilbity);
- **lifetime of the small scale flow**;
- **response time:** the time for small scale flow to respond and adjust (e.g., time for the initiation of convection);
- how quickly a small-scale flow can respond in reality and in “models”
- **feedback duration:** the period that small scale flow can provide feedbacks to large-scale flows (which should be less than its lifetime)

how long it will take for small-scale flows to have significant impact on the large-scale flow

For two-way scale interactions, accurate representation of “forcing” and its “control”, and simulations of “response” and its “feedback” are equally important!

Tropical Waves and TC Formation

By analyzing the NCEP-NCAR reanalyses (e.g., 850 and 200 hPa winds) and the outgoing longwave radiation data, Frank and Roundy (2006) found strong relationship between TC formation and enhanced activity in

- mixed Rossy Gravity (MRG) wave,
- TD-type disturbance (or easterly wave),
- equatorial Rossby wave,
- Madden-Julian Oscillation

In addition, they pointed out the possibility of detecting the convective anomalies of waves associated with genesis up to 1 month in advance.

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Challenges

Satellite Data Challenges:

o) Massive data storage
o) Display/visualizations (~TB)

Modeling Challenges:

o) Explicit representation of (the effects of) convective-scale motions
o) Verification of model simulations at high spatial and temporal resolutions
o) Understanding and representation of multiscale interactions

Computational Challenges:

o) Real-time requirements with supercomputing
o) Efficient data I/O (at runtime) and data access (via massive storage systems)
o) Parallel computing and parallel I/O with new processors (e.g., multi-cores)
o) Processing and visualizations of massive data volumes with large-scale multiple-panel display system

Satellite, Numerical Models, and Supercomputing Technology

NASA Major Supercomputers

Columbia Supercomputer (ranked 2nd 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
- **20 terabytes total memory;** 1 terabyte of memory per 512 processors

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

- **quad-core Xeon 5472 (Harpertown) CPUs,** speed - 3GHz; Cache - 12MB per CPU
- **81,920 cores in total** (512 cores per cabinet)
- **120+ TB memory in total,** 1 (8) GB memory per core (node)
- **3.1 PB disk spaces**
- **InfiniBand, 9,216 compute nodes**
- **973.4 Tflops/s peak; 722.7 Tflops/s Linpack**

Biswas, R., M.J. Aftosmis, C. Kiris, and **B.-W. Shen**, 2007: Petascale Computing: Impact on Future NASA Missions. Petascale Computing: Architectures and Algorithms, 29-46 (D. Bader, ed.), Chapman and Hall / CRC Press, Boca Raton, FL.

Concurrent Visualization System V2.0

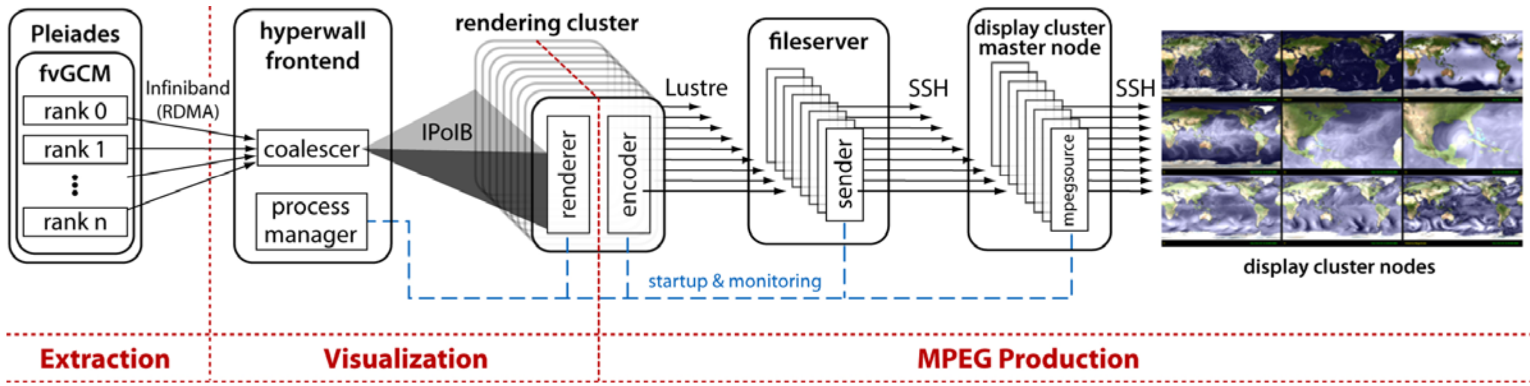


Figure : The newly developed Concurrent Visualization (CV) System (Version 2, top panel). Rounded rectangles indicate systems, and rectangles indicate processes. The whole system (from left to right panels) consists of a computing node ("Columbia Node"), a middle-layer system ("coalescer"), and the hyperwall-2 128-node 8-core/node rendering cluster. These systems are used for data extraction, handling, and visualization; and for MPEG image production and visualization display.

Shen, B.-W., W.-K. Tao, G. Bryan, C. Henze, P. Mehrotra, J.-L. F. Li, S. Cheung, 2009: High-impact Tropical Weather Prediction with the NASA CAMVis: Coupled Advanced multi-scale Modeling and concurrent Visualization Systems. Supercomputing conference 2009, Portland, Oregon, November 14-20, 2009.

Green, B., C. Henze, B.-W. Shen, 2010: Development of a scalable concurrent visualization approach for high temporal- and spatial-resolution models. AGU 2010 Western Pacific Geophysics Meeting, Taipei, Taiwan, June 22-25, 2010.

Shen, B.-W., W.-K. Tao, B. Green, 2010 Coupling NASA Advanced Multi-Scale Modeling and Concurrent Visualization Systems for Improving Predictions of Tropical High-Impact Weather (CAMVis). Submitted to IEEE Computing in Science and Engineering **(accepted)**

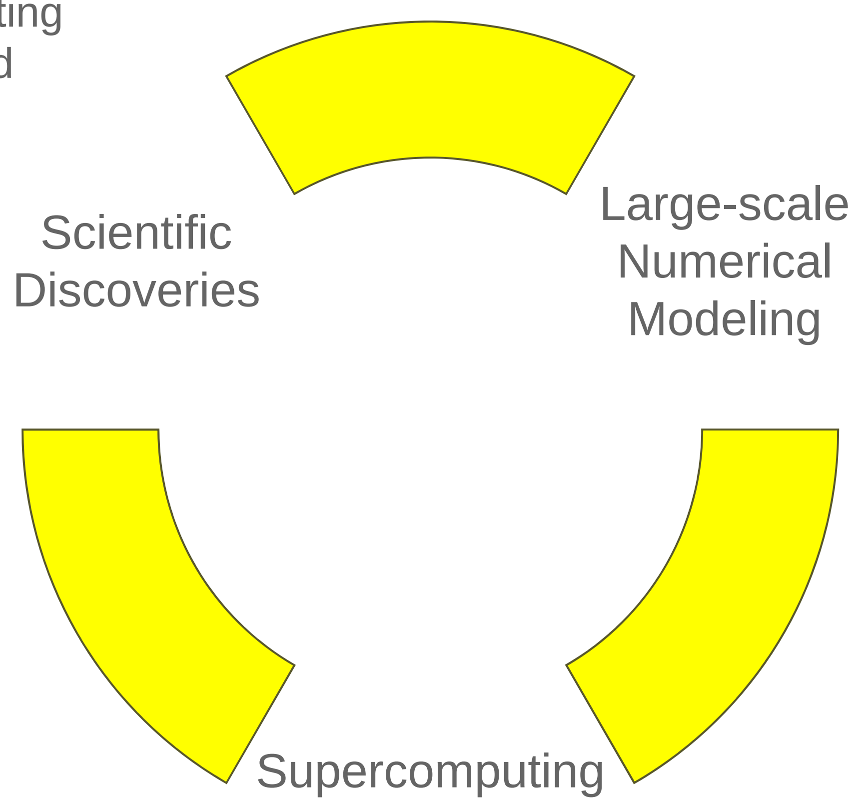
Resolutions vs. Model Grid Cells

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

A Science-Driven Approach

Goals:

- **to explore** the power of supercomputing technology (e.g., supercomputers and visualization systems) on the advancement of global 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)
- **to extend** the lead-time of hurricane predictions (and high-impact tropical weather predictions): from short-term (~5days) to extended-range (15~30 days) forecasts



In short, to advance numerical models and thus to extend the lead time of hurricane predictions with modern supercomputing technology

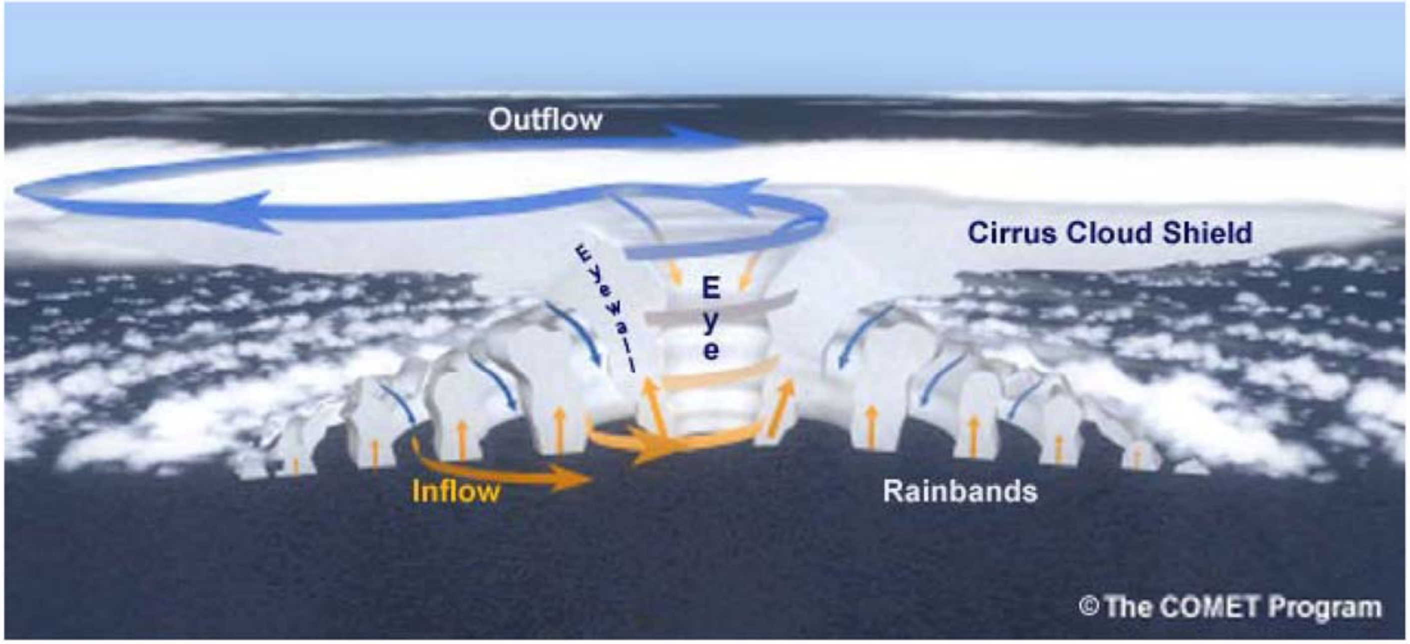
The Global Mesoscale Model

Model Dynamics and Physics:

- The finite-volume dynamical core (Lin 2004);
- The NCAR physical parameterizations, and NCEP SAS as an alternative cumulus parameterization scheme
- The NCAR land surface model (CLM2, Dai et al. 2003)

Computational design, scalability and performance (suitable for running on clusters or multi-core systems)

Hurricane ABC



1. **Eye:** A region in the center of a hurricane (tropical storm) where the winds are light and skies are clear to partly cloudy.
2. **Eyewall:** A wall of dense thunderstorms that surrounds the eye of a hurricane.
3. **Low Inflow:** counter clockwise circulation
4. **Upper Outflow:** clockwise circulation
5. **Elevated warm-core:** At a given level in the atmosphere, the cyclone's temperature is warmer at its center than at its periphery

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Highlights of Research Papers in 2010

A series of papers which have been published or are being prepared show that the lead time of TC formation prediction can be extended by improving the simulation of large-scale tropical waves and their multiscale interactions using the NASA high-resolution global modeling and supercomputing technologies. Examples include

- Very severe cyclonic storm Nargis (2008) and its association with an Equatorial Rossby wave (Shen et al., 2010a);
- **Hurricane Helene (2006) and its association with an African Easterly wave (Shen et al., 2010b);**
- Twin tropical cyclones in May 2002 and their association with a mixed Rossby gravity wave (Shen et al., 2010d)

To verify model's performance, NASA observations from filed campaign (such as NAMMA) and satellites at comparable resolutions (e.g., QuikSCAT and TRMM) are used for inter-comparisons (Shen et al., 2010a,b,c,d).

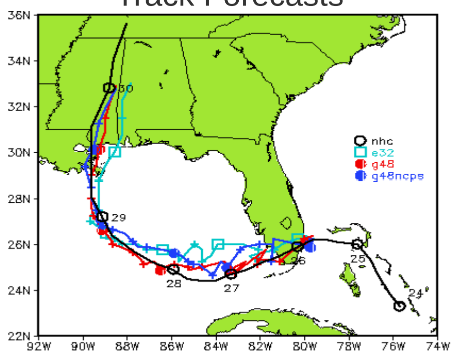
Forecasts of Katrina's Track, Intensity, Structures

(Shen et al., 2006b, Geophys. Res. Lett., L13813, doi:10.1029/2006GL026143)

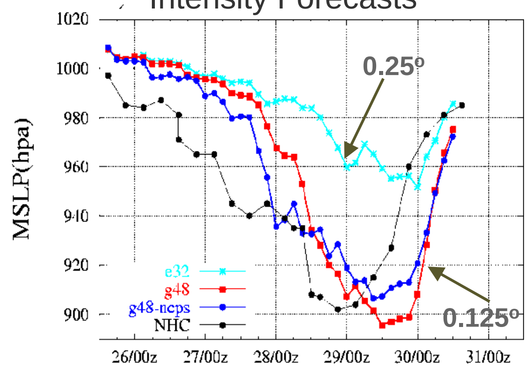
Selected as Journal Highlight by American Geophysical Union
Featured in *Science* magazine (August, 2006)
Featured in the 2006 Annual report of SAIC (Science Application International Corp.)

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

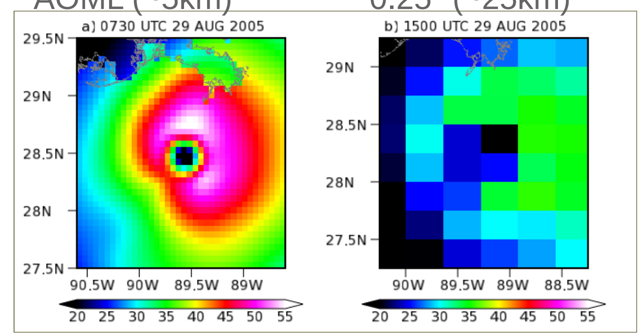
Track Forecasts



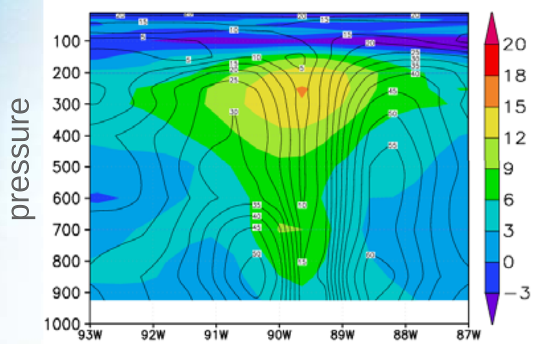
Intensity Forecasts



AOML (~5km) 0.25º (~25km)

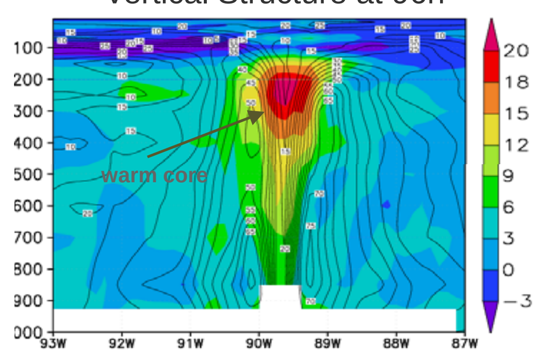


Vertical Structure (NCEP)



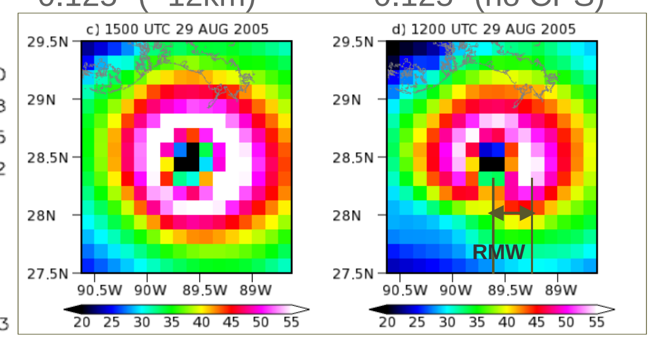
GFS Analysis (~35km) valid at 08/29/12z

Vertical Structure at 96h



96 h Simulations with no CPS

0.125º (~12km) 0.125º (no CPS)

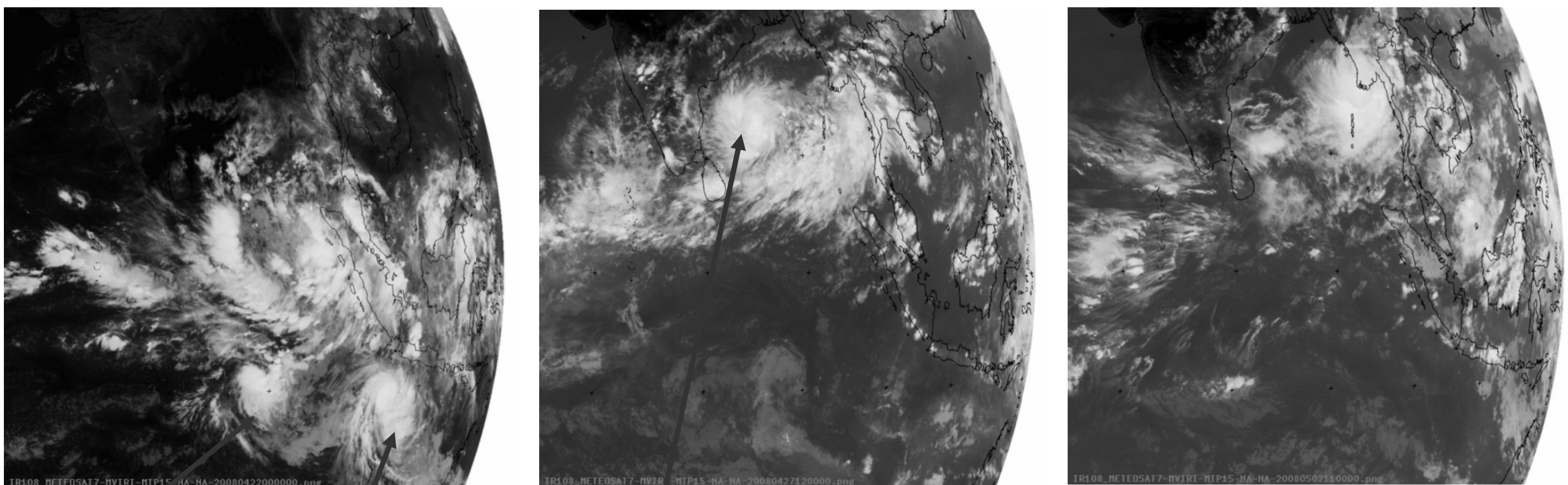


Near-eye Wind Distributions in a 2ºx2º box from 96h simulations, validated at 08/29/12z.

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

Very Severe Tropical Storm Nargis (2008)

00Z Apr 22 | 12z Apr 27 | 11z May 2



Durga (22-24 Apr)

Rosie (21-24 Apr)

Formation of Nargis

Landfall in Myanmar

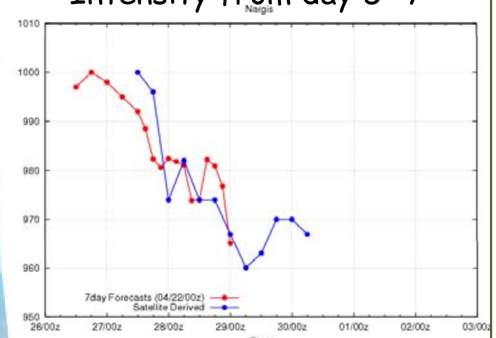
Shen, B.-W., W.-K. Tao, W. K. Lau, R. Atlas, 2010a: Predicting Tropical Cyclogenesis with a Global Mesoscale Model: Hierarchical Multiscale Interactions During the Formation of Tropical Cyclone Nargis (2008) . J. Geophys. Res., doi:10.1029/2009JD013140.

Multiple processes and their scale interaction

(Shen et al., 2010a, JGR,)

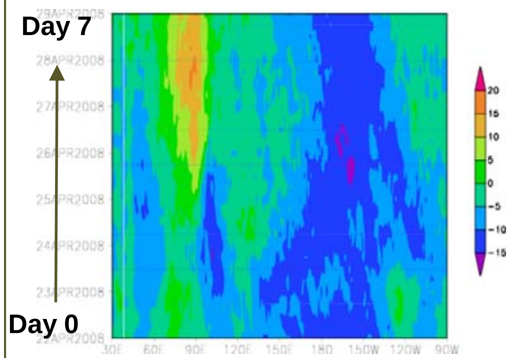
7-day global multiscale simulations suggest the following favorite factors for the formation and initial intensification of tropical cyclone Nargis:

Intensity from day 5 -7



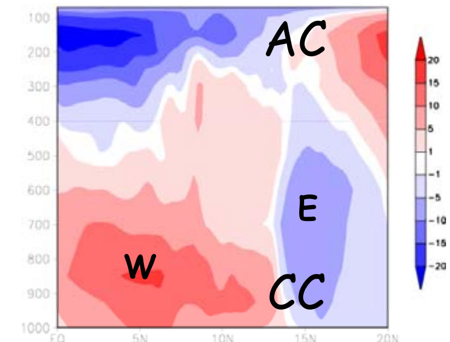
Time evolution of simulated min SLP (red) from day 5 to day 7, as compared to the satellite observation

N. movement of WWB



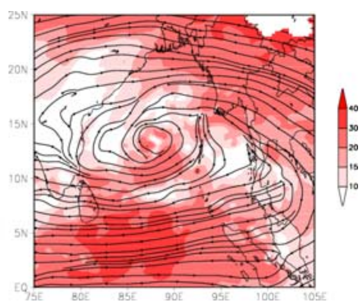
Time/longitude diagram of zonal winds averaged over latitude 5°N to 10°N. West Wind Belt/Burst (WWB) is indicated by orange area. (Northward movement is clearly shown as the above is compared to the one averaged latitude 5S° to the equator.)

Monsoonal circulation



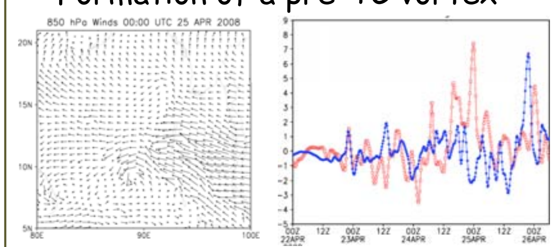
Altitude/latitude cross section of zonal winds averaged over longitude 80°E-90°E. Westerly and early winds are shown in red and blue. Weak vertical wind shear is indicated by the "vertical orientation of the white line". Middle- and Low-level cyclonic circulation (CC) and upper-level anti-cyclonic circulation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

AC wind shear



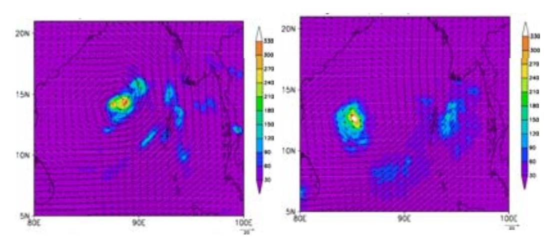
126h simulation of vertical wind shear between 850- and 200-hap, showing anti-cyclonic wind shear and good upper-level outflow

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

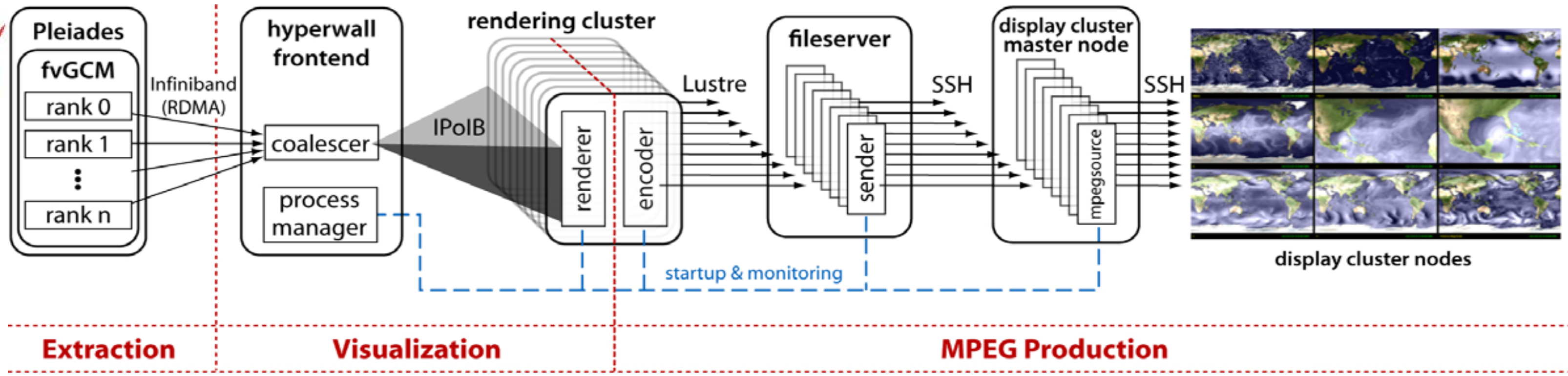
Vortex circulation and precip



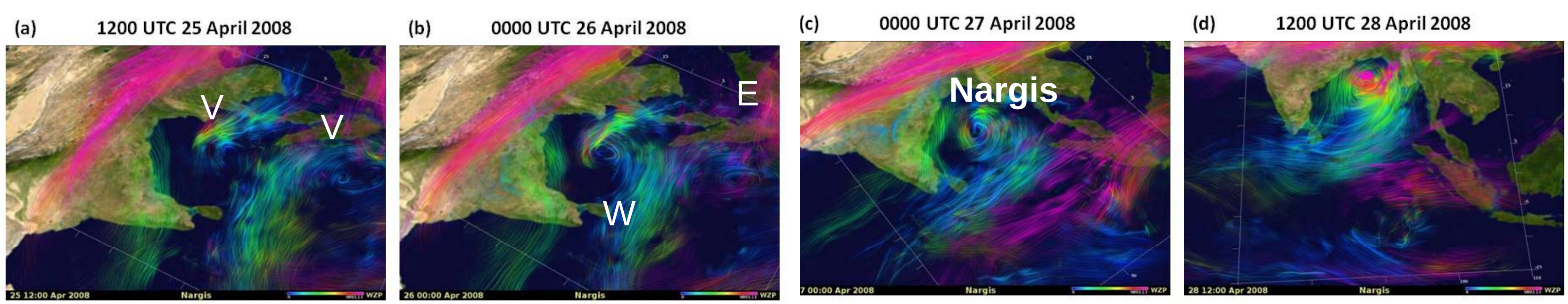
Averaged precip and 850-hPa winds from day 5 to day 7 (left) and averaged NASA TRMM precip and NCEP Reanalysis winds (right)

3D Visualization with the NASA CAMVis

(Shen et al., 2010c, CiSE, accepted)

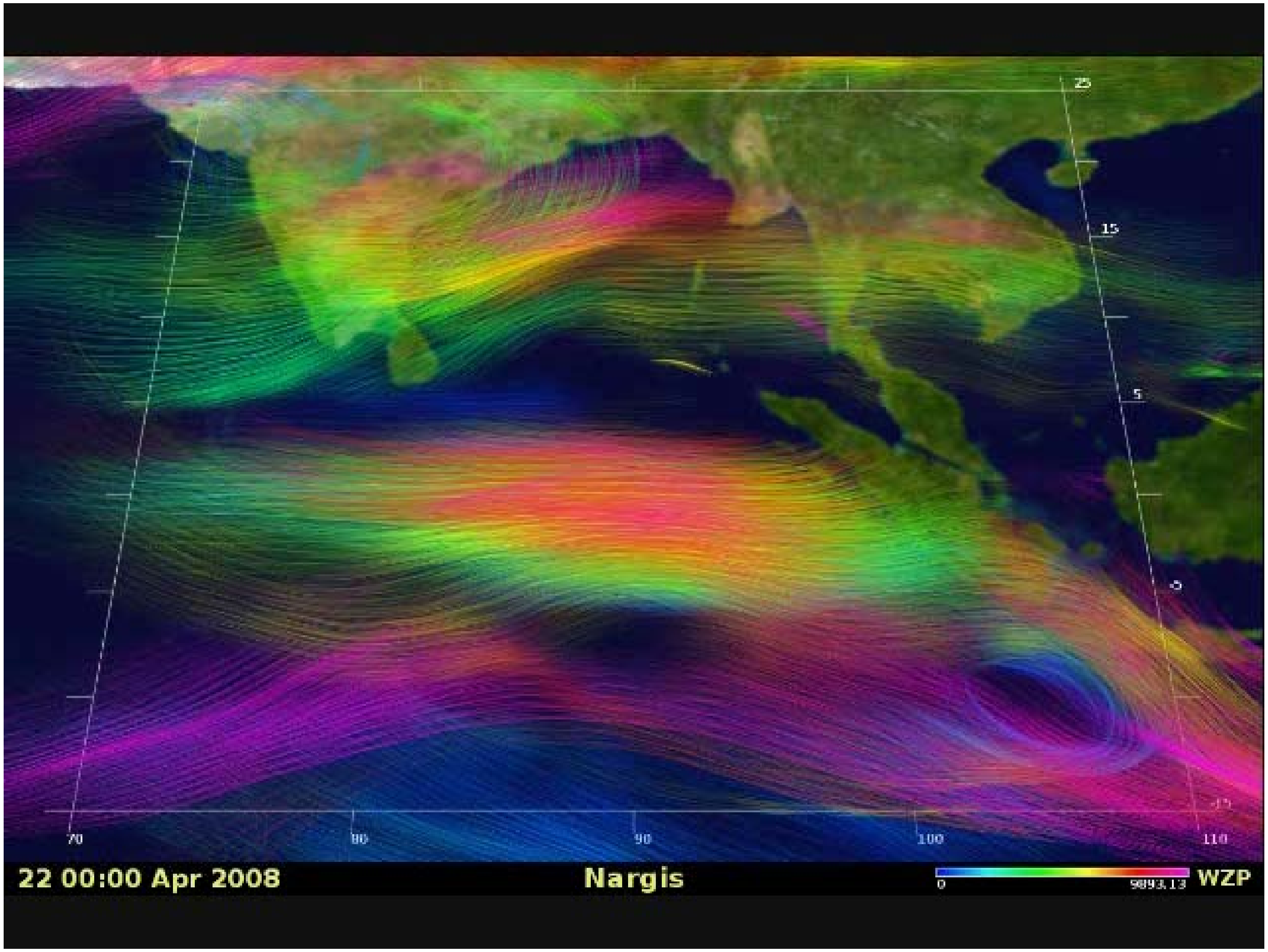


The newly developed Concurrent Visualization (CV) System. Rounded rectangles indicate systems, and rectangles indicate processes. The whole system (from left to right panels) consists of a computing node (“Pleiades Node"), a middle-layer system ("coalescer"), and the hyperwall-2 128-node 8-core/node rendering cluster. These systems are used for data extraction, handling, and visualization; and for MPEG image production and visualization display.



Realistic 7-day simulations of the formation of TC Nargis (2008) initialized at 0000 UTC April 22, 2008. Low-level winds are in blue and upper-level winds in red: (a) formation of a pair of low-level vortices (labeled in ‘V’) at 84h simulation. (b) intensification of the northern vortex (to the left) (c); formation of TC Nargis associated with the enhancement of the northern vortex; (d) intensification of TC Nargis associated with upper-level outflow and moist processes, indicated by the enhanced upper-level outflow circulation. 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).

Animation of Nargis Formation



Simulations of Twin Tropical Cyclones

Previous studies suggest that twin tropical cyclones (TCs), symmetric with respect to the equator, may occur associated with large-scale equatorial tropical waves and 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.

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

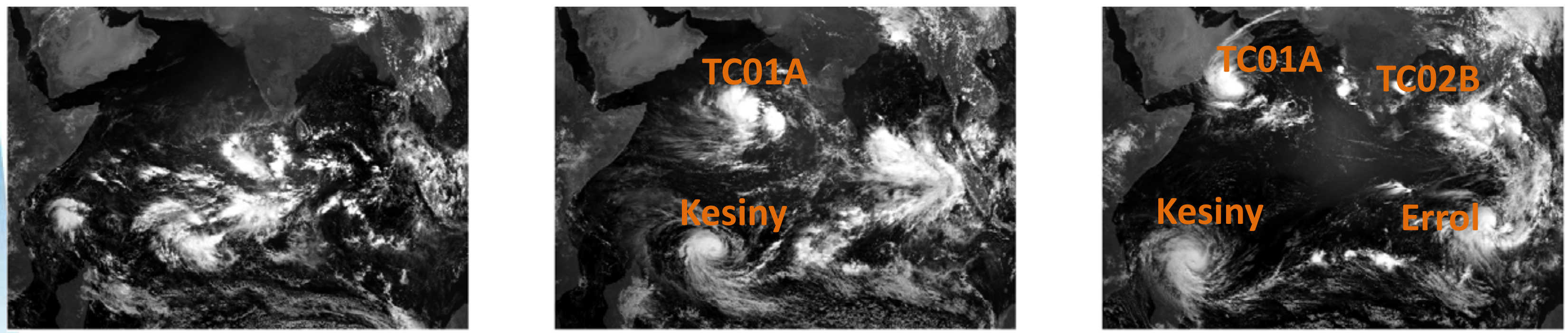
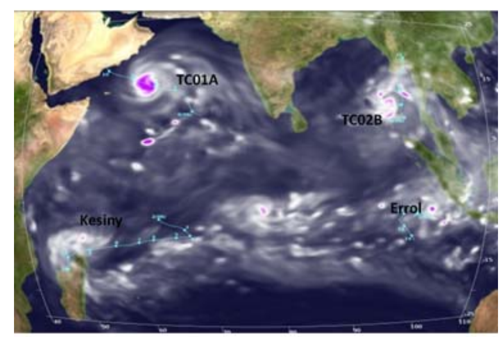


*Figure : Predictions regarding the formation of twin tropical cyclones in the Indian Ocean: (a) MJO-organized convection over the Indian Ocean at 0630 UTC 1 May 2002. When the MJO moved eastward, two pairs of twin TCs appeared sequentially on 6 May (b) and 9 May (c), including TC 01A, Kesiny, TC 02B and Errol. Two TCs (01A and 02B) with anti-clockwise circulation appeared in the Northern Hemisphere, while 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.**, 2010d for details).*

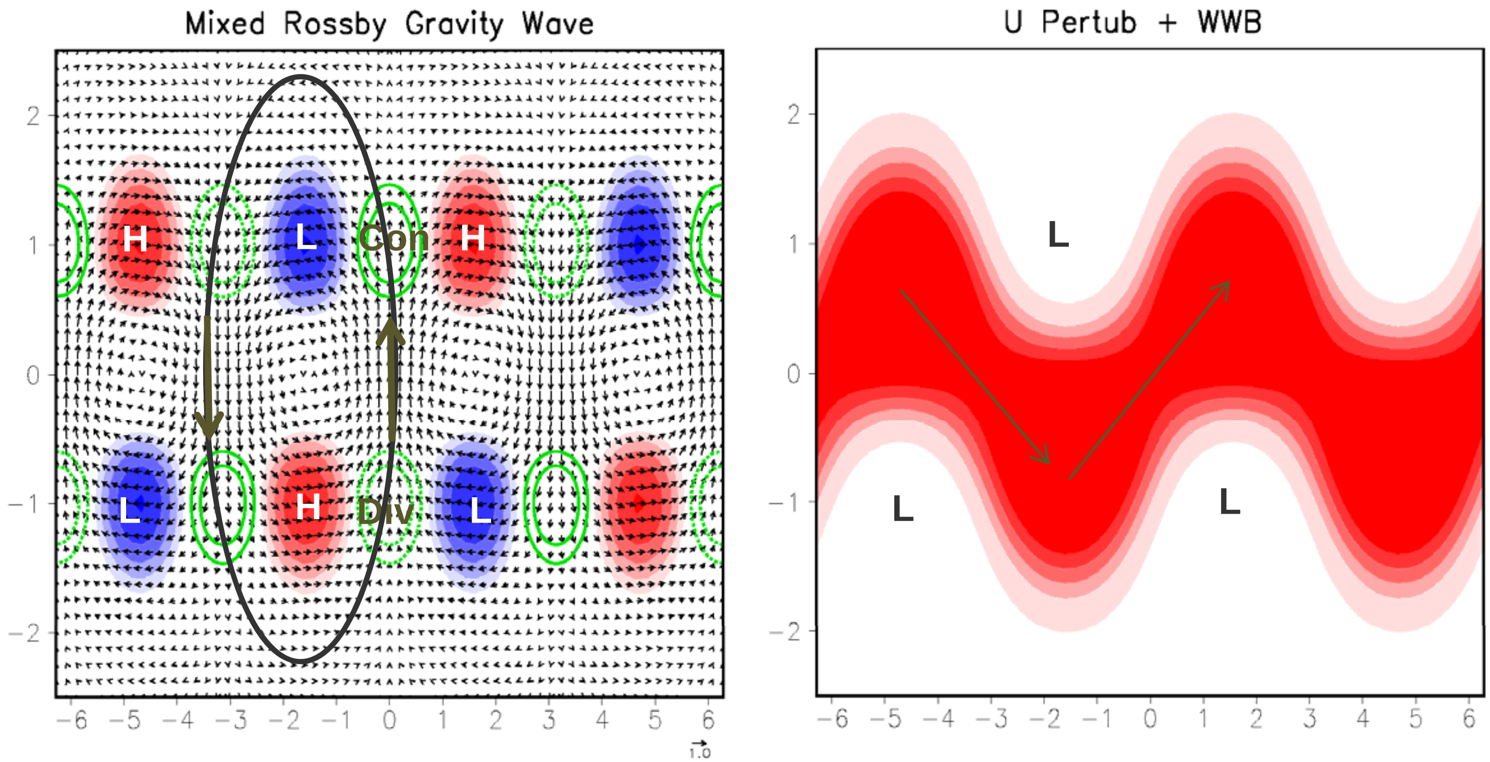


Shen, B.-W., W.-K. Tao, et al. 2010d: Genesis of Twin Tropical Cyclones Revealed by a Global Mesoscale Model: the Role of Mixed Rossby Gravity Wave (to be submitted in December, 2010)

mixed Rossby gravity (MRG) wave

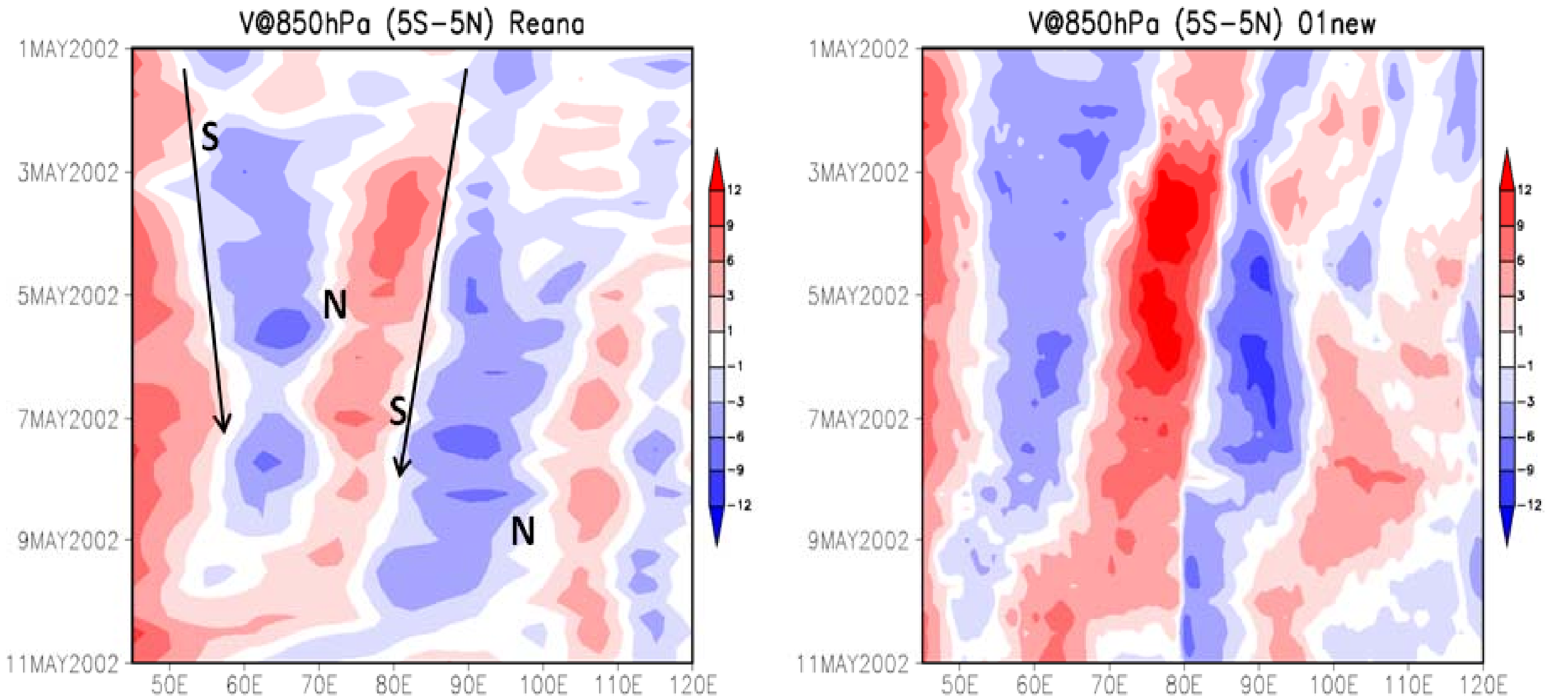
- The MRG wave has maximum/minimum of meridian winds at the equator (cross equatorial flow)
- It appears primarily in the spectral range of 4-5 days period
- It is anti-symmetric about the equator
- A free mode is barotropic while a forced MRG wave has phase lines tilting with height;
- The thermal forcing for the observed waves is apparently supplied by the diabatic heating due to cumulonimbus convection organized by the large-scale flow (Holton, 1975)
- It has been suggested that the low level moisture convergence due to this inviscid wave wind field can excite an instability (called “wave-CISK”), → which can be used to explain the 4-5 day periodicity (Lindzen)

Analytic Solutions for a MRG Wave



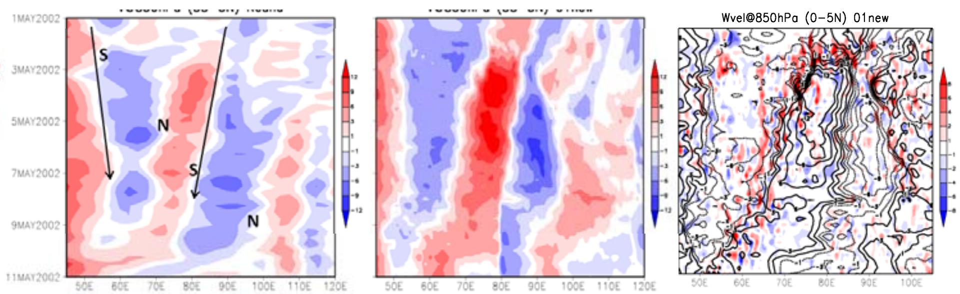
(a) Normalized analytic solution for the perturbation of horizontal winds (vector), geopotential heights (shaded; positive in red and negative in blue) and convergence (contour in green; positive in solid lines; negative in dashed lines). (b) Summation of zonal winds associated with an MRG wave and westerly wind bursts. Main features include cross equatorial flows; alternating cyclonic and anti-cyclonic circulations; asymmetry of winds and geopotential heights with respect to the equator. The low geopotential heights (shaded in red) leads the convergence (contour in solid green lines) by 1/4 wavelength.

Time/longitude diagram of meridian winds



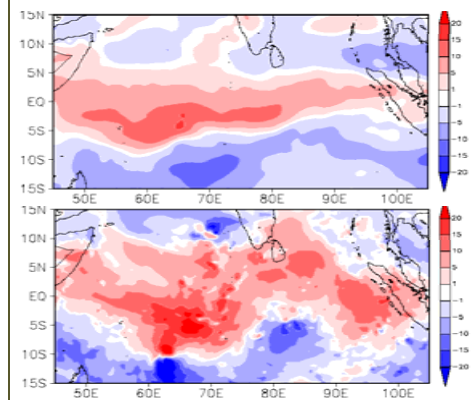
Interactions of Twin TCs and MRG wave (shen et al., 2010d)

Wavelength reduction of mixed Rossby gravity (MRG) wave



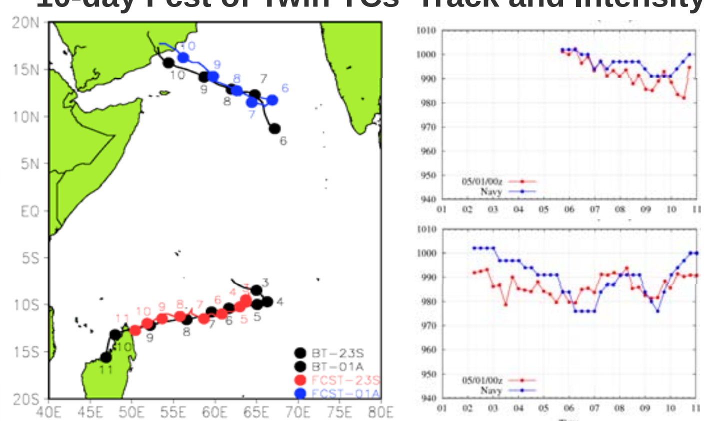
Time/longitude diagram of meridian winds from NCEP analyses (a) and the 10-day control run (b). Northerly (southerly) winds are indicated in red (blue). The westward-propagating disturbances with the sloping northerly to southerly flow couplets that are nearly asymmetric about the equator are likely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

MRG Wave Development



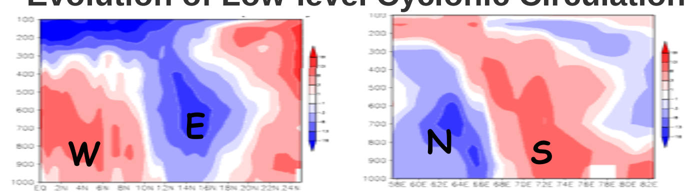
Simulations of 850-hPa zonal winds at the initial time and the integration of 96 hours.

10-day Fcst of Twin TCs' Track and Intensity



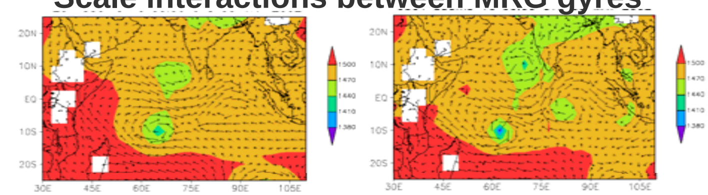
Track (a) and Intensity simulations of TCs 01A (b) and 23S (c) from the 10-day run initialized at 00Z 1 May 2002, as compared to observations. The first record for TC 23S (01A) was issued at 06Z 3May (18Z 5 May).

Evolution of Low-level Cyclonic Circulation



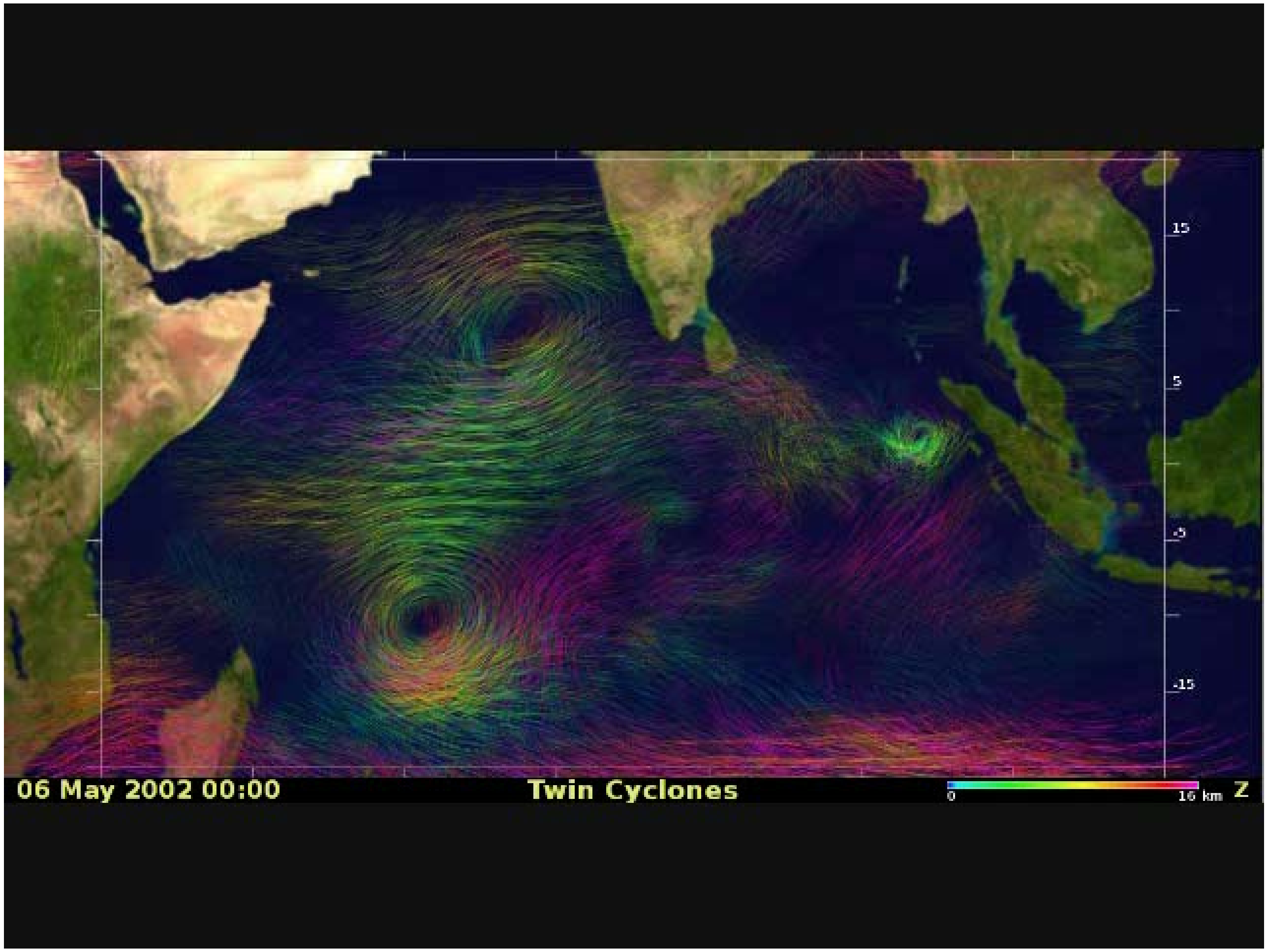
120h simulations of zonal (left) and meridian winds (right)

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).

Formation of Twin Tropical Cyclones



Shen, B.-W., W.-K. Tao, et al., 2010d: Forecasting Tropical Cyclogenesis with a Global Mesoscale Model: Preliminary Results for Twin Tropical Cyclones in May 2002. (to be submitted)

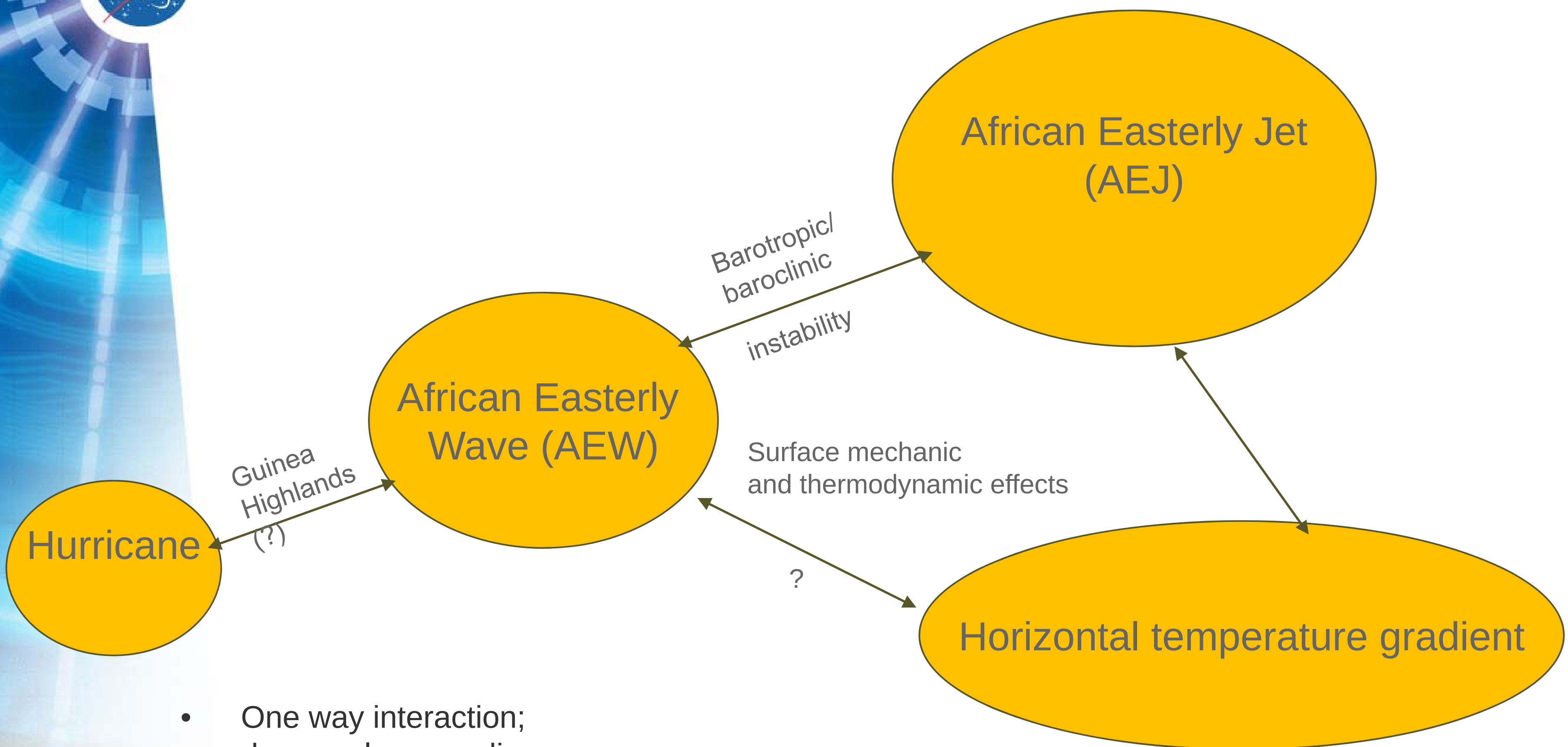
African Easterly Waves (AEWs)

- 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). Nearly 85% of intense hurricanes have their origins as AEWs [e.g., Landsea, 1993]. 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.

African Easterly Jet (AEJ)
(Thorncroft and Blackburn, 1999)

- AEJ is a midtropospheric jet located over tropical north Africa during the northern hemisphere summer
- AEJ is seen as a prominent feature in the zonal wind, with a maximum of around 12.5 m/s at 600-700 hPa and 15^{o}N.
- Its vertical shears are crucial in organizing moist convection and generation of squall lines;
- Its horizontal and vertical shears are important for the growth of easterly waves;
- Below the AEJ, the easterly wind shear is in thermal wind balance with the surface temperature gradient (BWS)
- One may view the AEJ as resulting from the combination of diabatically forced meridional circulations which maintain it and easterly waves which weaken it. As the nature of diabatic forcing (e.g., moist or dry convection) differs between models, simulated AEJ is likely to be different (e.g., different heights and/or strengths, which will subsequently affect the easterly waves -→ model climate
- The rate at which the AEJ is maintained is likely to be particularly sensitive to the boundary layer parameterization
- Other factors should be included: radiation; the establishment of the surface temperature and humidity gradients themselves; etc

Multiscale Interaction during Hurricane Formation



- One way interaction;
- downscale cascading;
- no or limited feedbacks from smaller-scale flows

Map of North Africa

Berry and Thorncroft (2005, MWR)

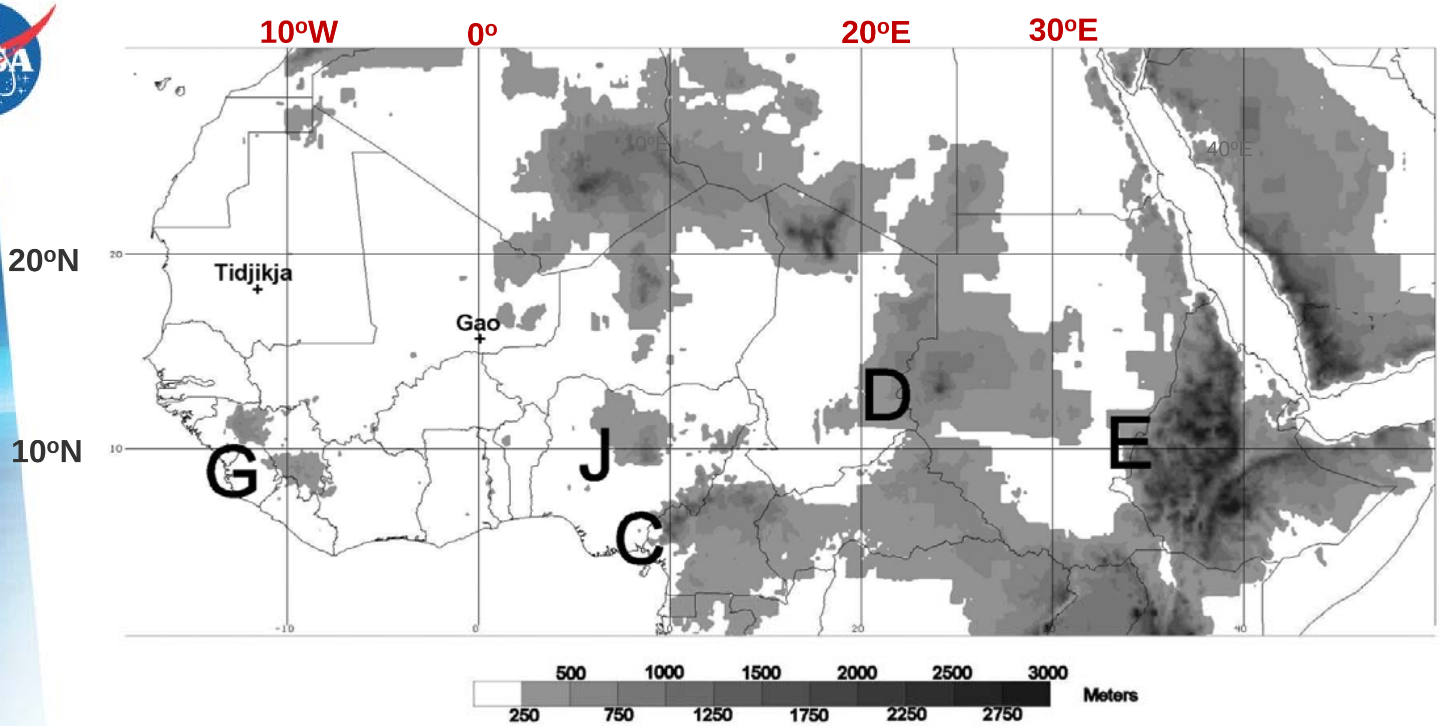
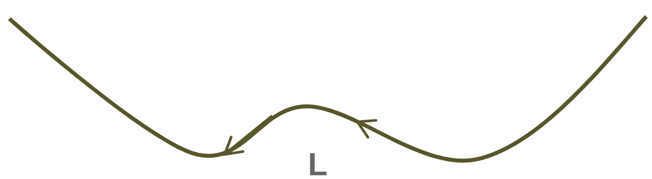


FIG. 1. Map of North Africa, including coastline and national borders. Relief over 250 m is shaded, with key at the bottom of the figure. Labels on the western side of orography identify the following regions: G = Guinea highlands, J = Jos Plateau, C = Cameroon highlands, D = Darfur highlands, and E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

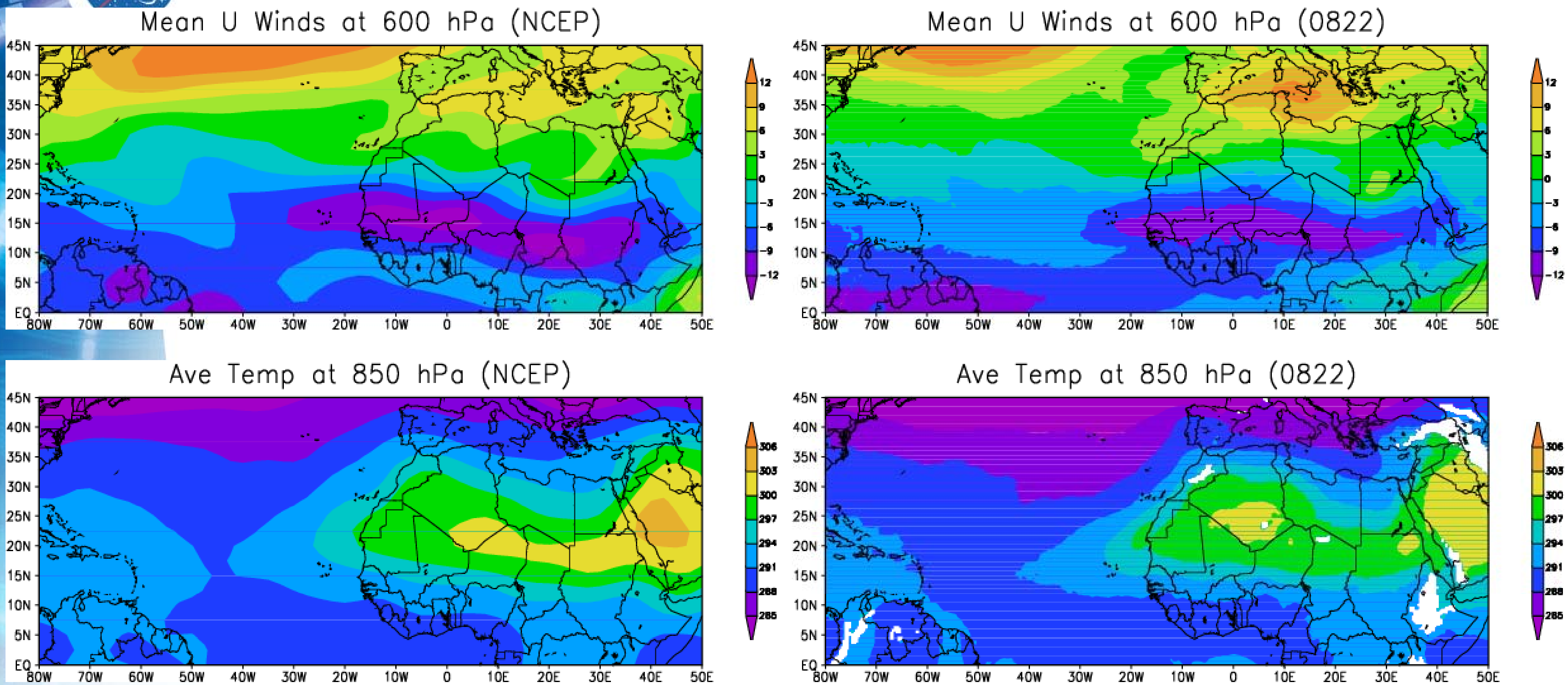


30-day Averaged U Winds and Temp

(init at 08/22/00z)

NCEP Reanalysis

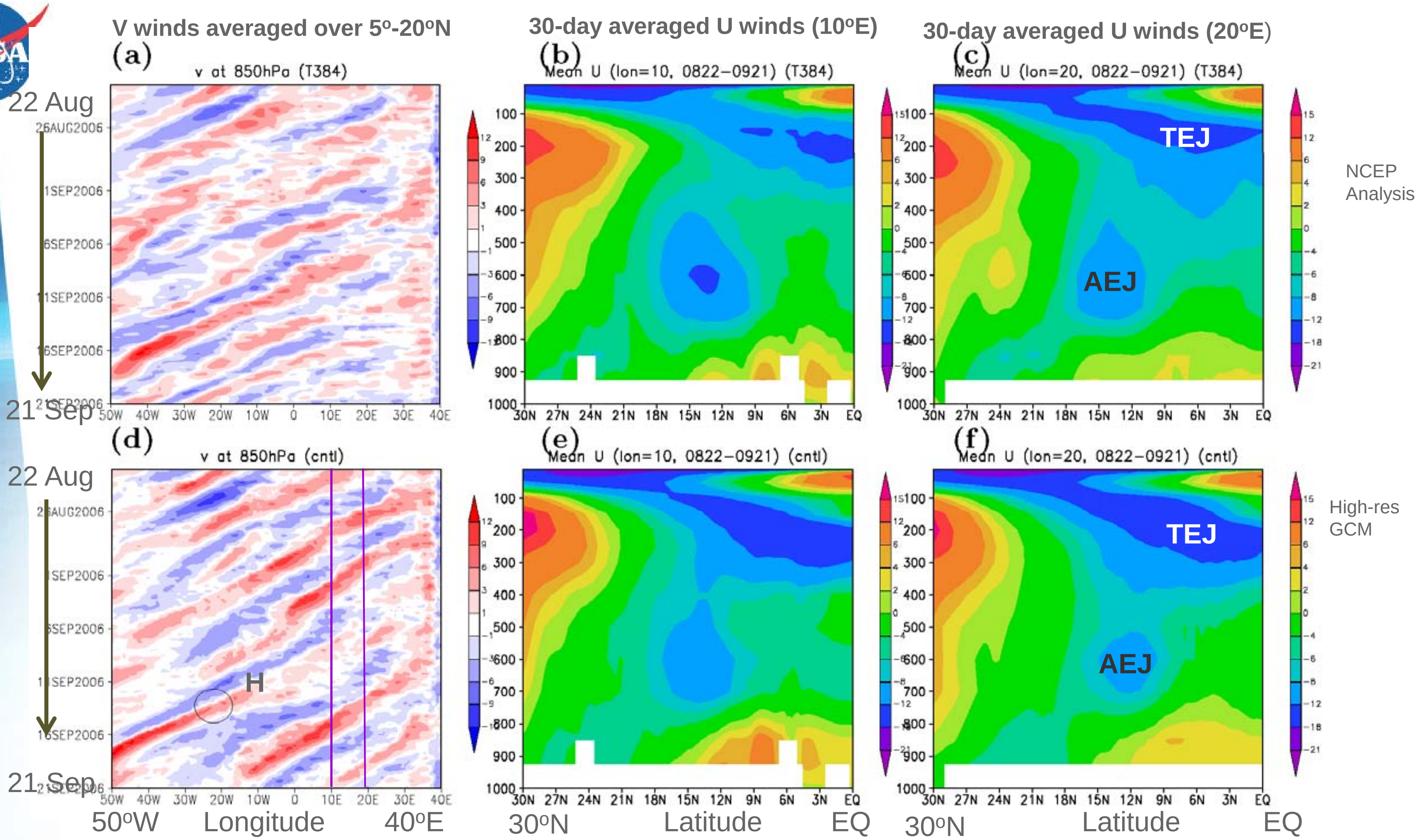
Model Simulations



Shen, B.-W. et al., 2010b: African Easterly Waves and African Easterly Jet in 30-day High-resolution Global Simulations. A Case Study during the 2006 NAMMA period. Geophys. Res. Lett., L18803, doi:10.1029/2010GL044355.

Five AEWs in 30-day Simulations

(init at 00zz Aug 22, 2006)

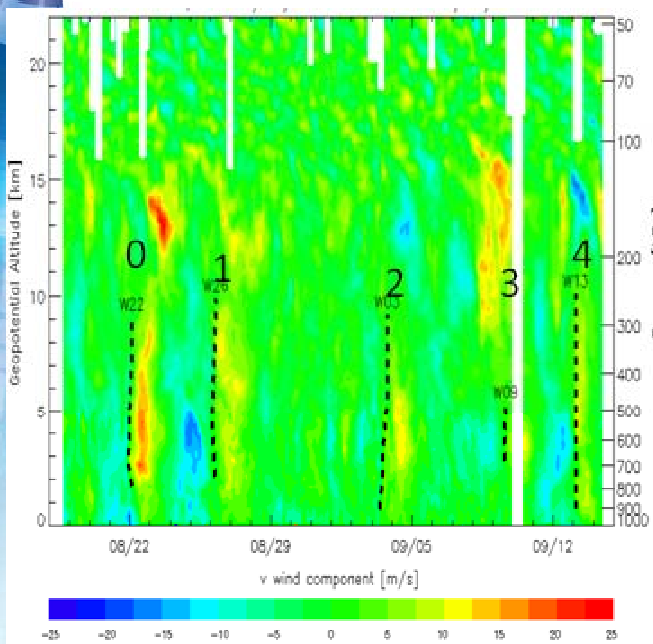


Shen, B.-W., W.-K. Tao, M.-L. Wu, 2010c: African Easterly Waves and African Easterly Jet in 30-day High-resolution Global Simulations. A Case Study during the 2006 NAMMA period. Geophys. Res. Lett., L18803, doi:10.1029/2010GL044355.

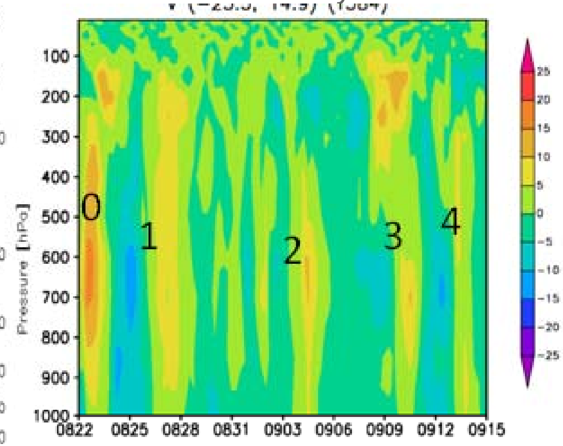
Verification with NAMMA Observations

Praia, CV @ (23.5ºW, 14.9ºN)

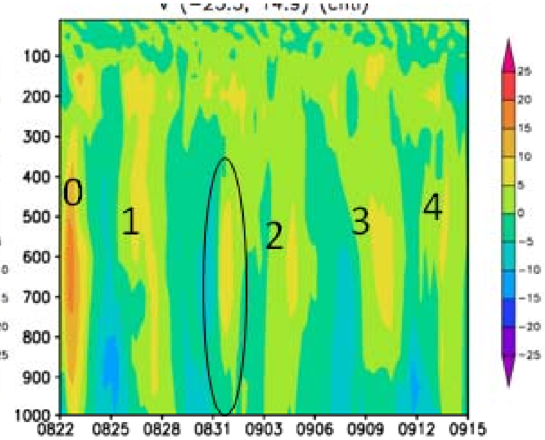
NAMMA OBS



NCEP Reanalysis



Model simulation



Left panel: Schmidlin, F. J., B. Morrison, T. Baldwin, E. T. Northam, 2007: High Resolution Radiosonde Measurements from Cape Verde: Details of Easterly Wave Passage. AGU 2007 Fall Meeting.

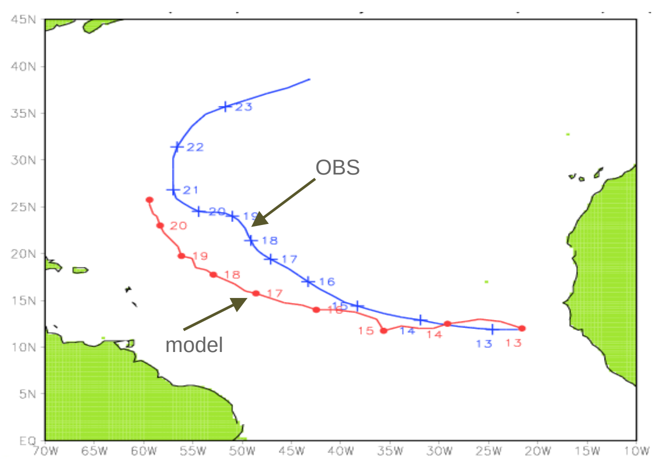
NAMMA: NASA African Monsoon Multidisciplinary Analyses

Shen, B.-W. et al., 2010b: African Easterly Waves and African Easterly Jet in 30-day High-resolution Global Simulations. A Case Study during the 2006 NAMMA period. Geophys. Res. Lett., L18803, doi:10.1029/2010GL044355.

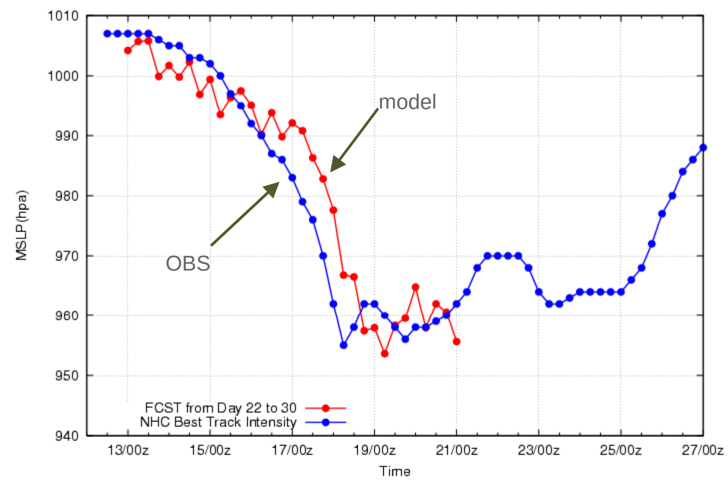
Simulations of Helene (2006) between Day 22-30

Helene: 12-24 September, 2006

Track Forecast



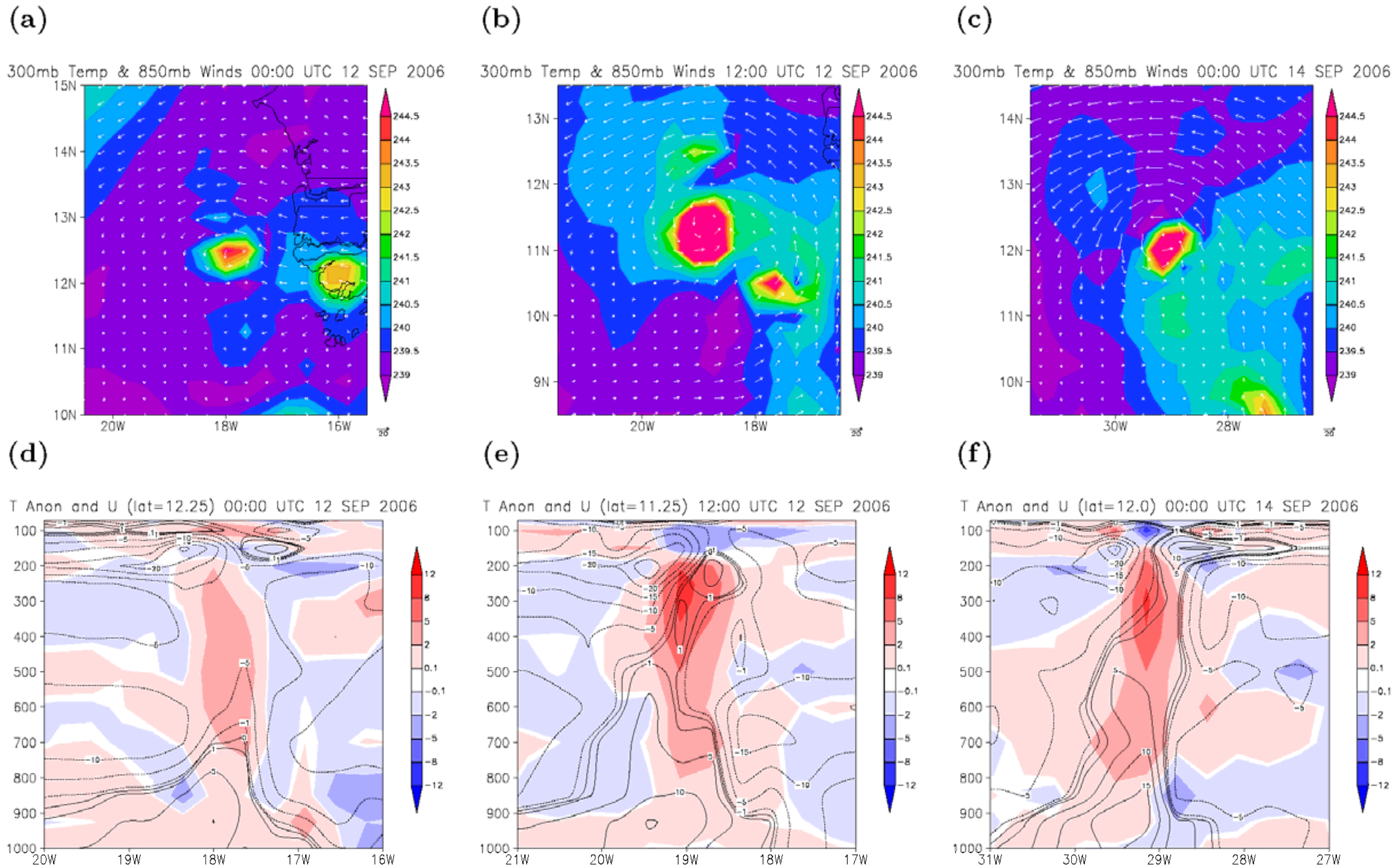
Intensity Forecast



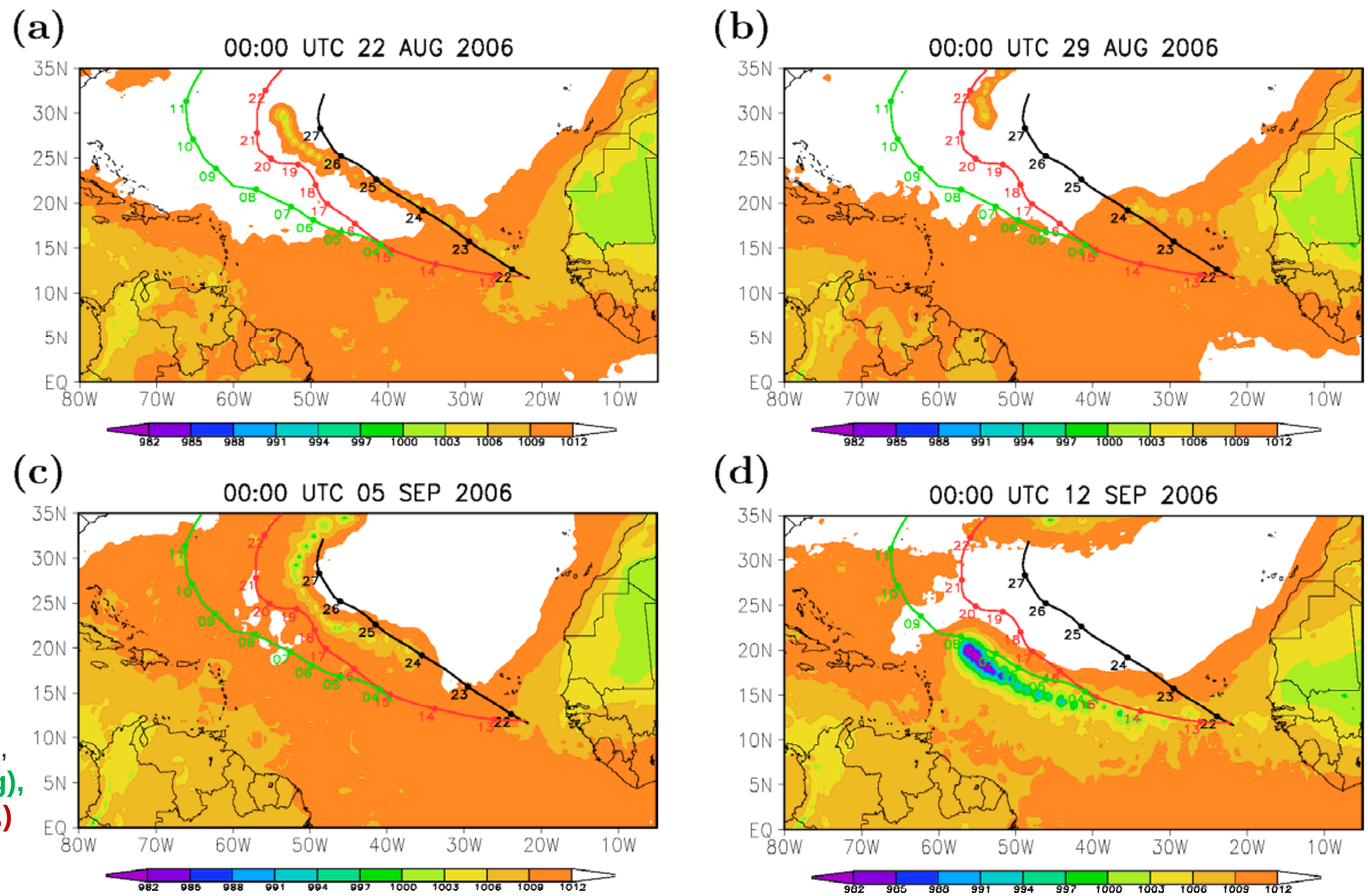
Future work:
to study multiscale interactions among TEJ, AEJ, AEWs, hurricanes and surface mechanic and thermodynamic processes

Shen, B.-W. et al., 2010b: African Easterly Waves and African Easterly Jet in 30-day High-resolution Global Simulations. A Case Study during the 2006 NAMMA period. Geophys. Res. Lett., L18803, doi:10.1029/2010GL044355.

Formation of an Elevated Warm Core



Formation of Multiple Hurricanes in a 30-day run



Debby (22-27 Aug),
Florence (3-12 Aug),
Helene (12-24 Sep.)

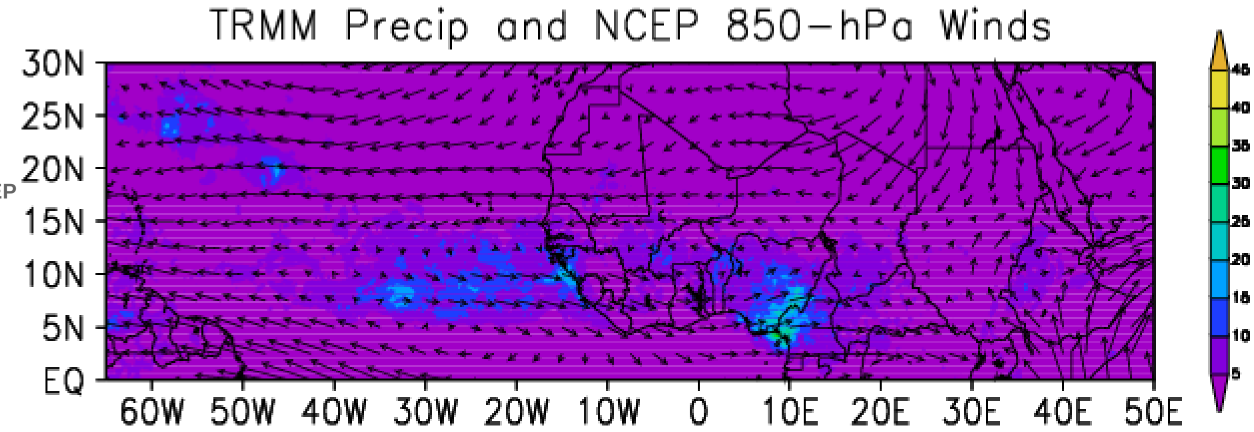
consistent with the 30-day averaged winds

Spatial distribution of minimum sea level pressure in a 7-day period

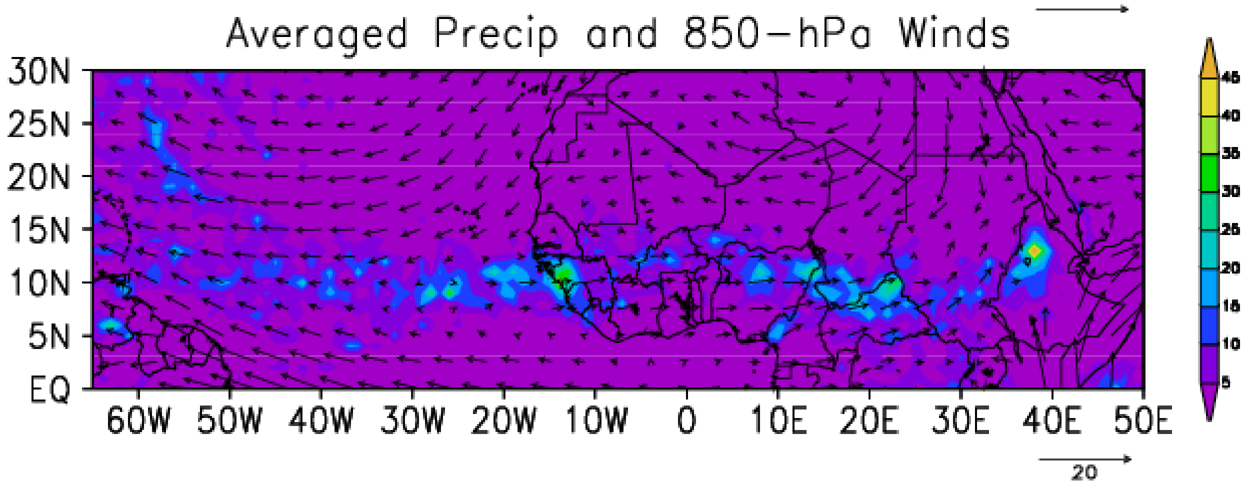
30-day Averaged Precip and 850 hPa Winds

(init at 08/22/00z)

TRMM Precip and NCEP Aeanalysis Winds

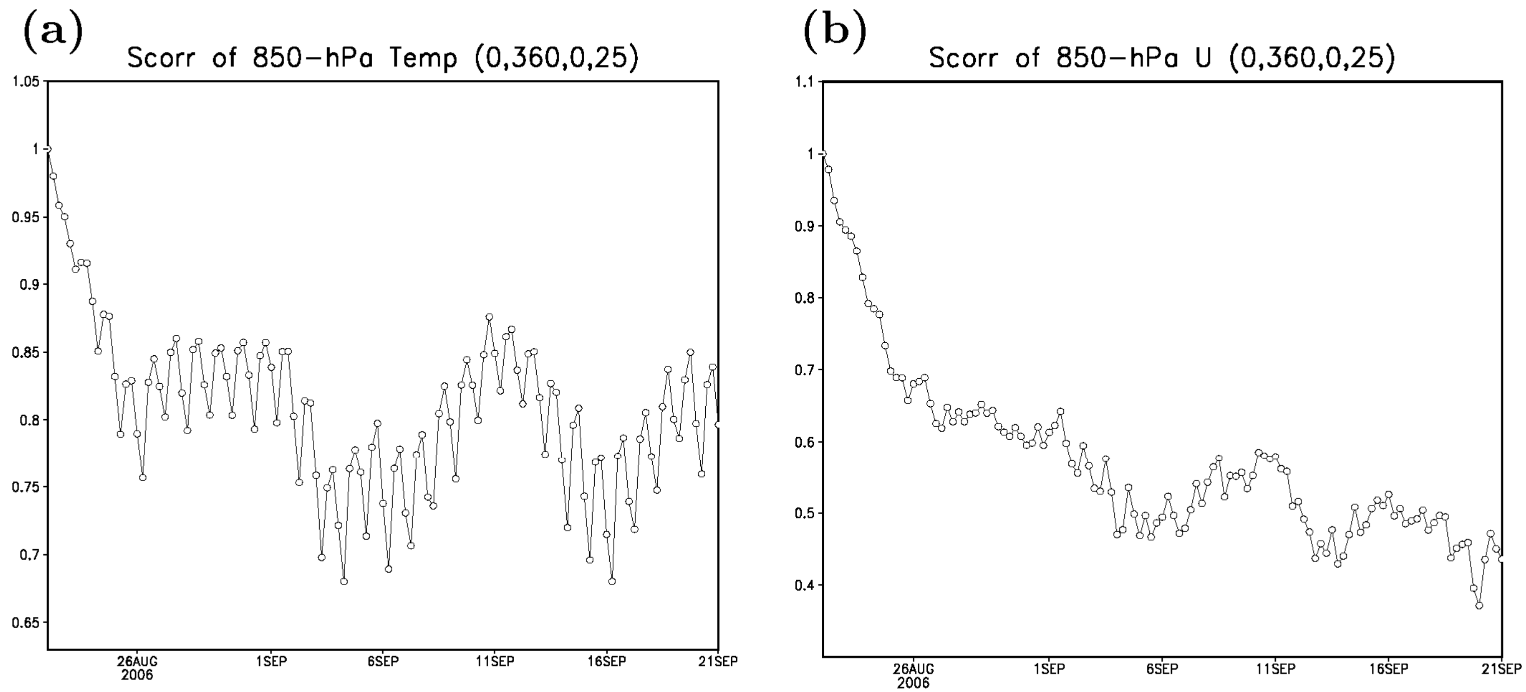


Model Simulations



Shen, B.-W. et al., 2010b: African Easterly Waves and African Easterly Jet in 30-day High-resolution Global Simulations. A Case Study during the 2006 NAMMA period. Geophys. Res. Lett., L18803, doi:10.1029/2010GL044355.

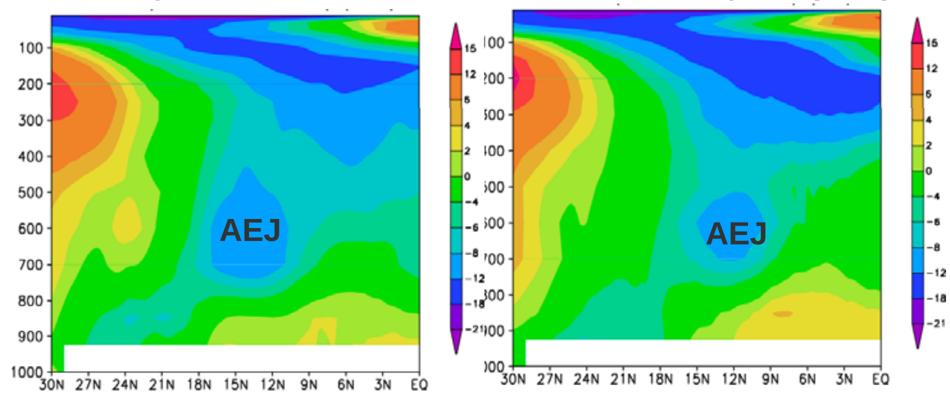
Correlation coefficients



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

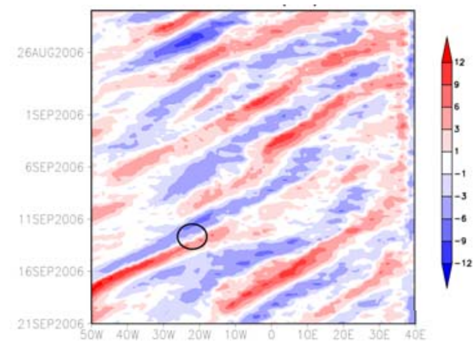
(Shen et al., 2010b, GRL)

Analysis and Simulation of African Easterly Jet (AEJ)



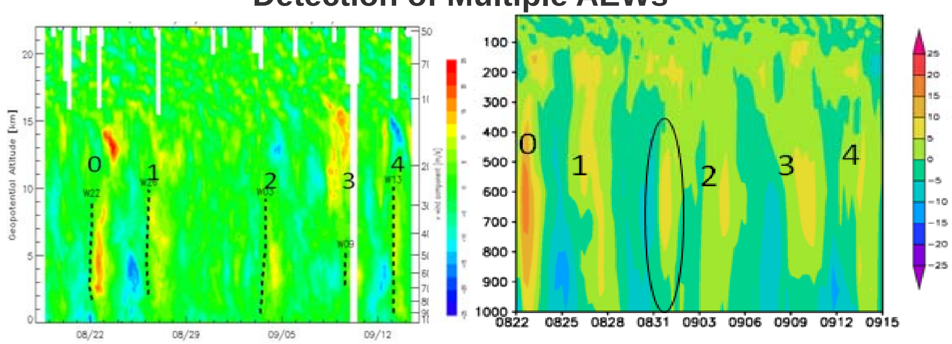
A 30-day averaged African Easterly Jet (AEJ) along longitude 20°E from GFS analysis (left) and a 30-day simulation (right) initialized at 0000 UTC August 22, 2006

African Easterly Waves (AEWs)



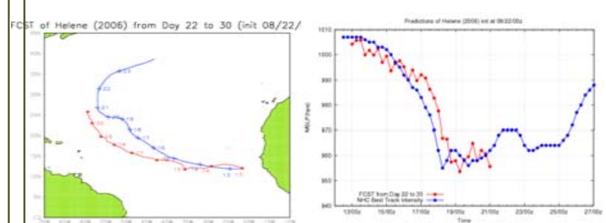
Six African Easterly Waves (AEWs) in a 30-day simulation . The black circle roughly indicates the timing and location of Helene's formation.

Detection of Multiple AEWs



Time-altitude cross sections of meridional winds at (23.5°W, 14.9°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 tracks, respectively.

NAMMA OBS by Zipser et al. (2009)

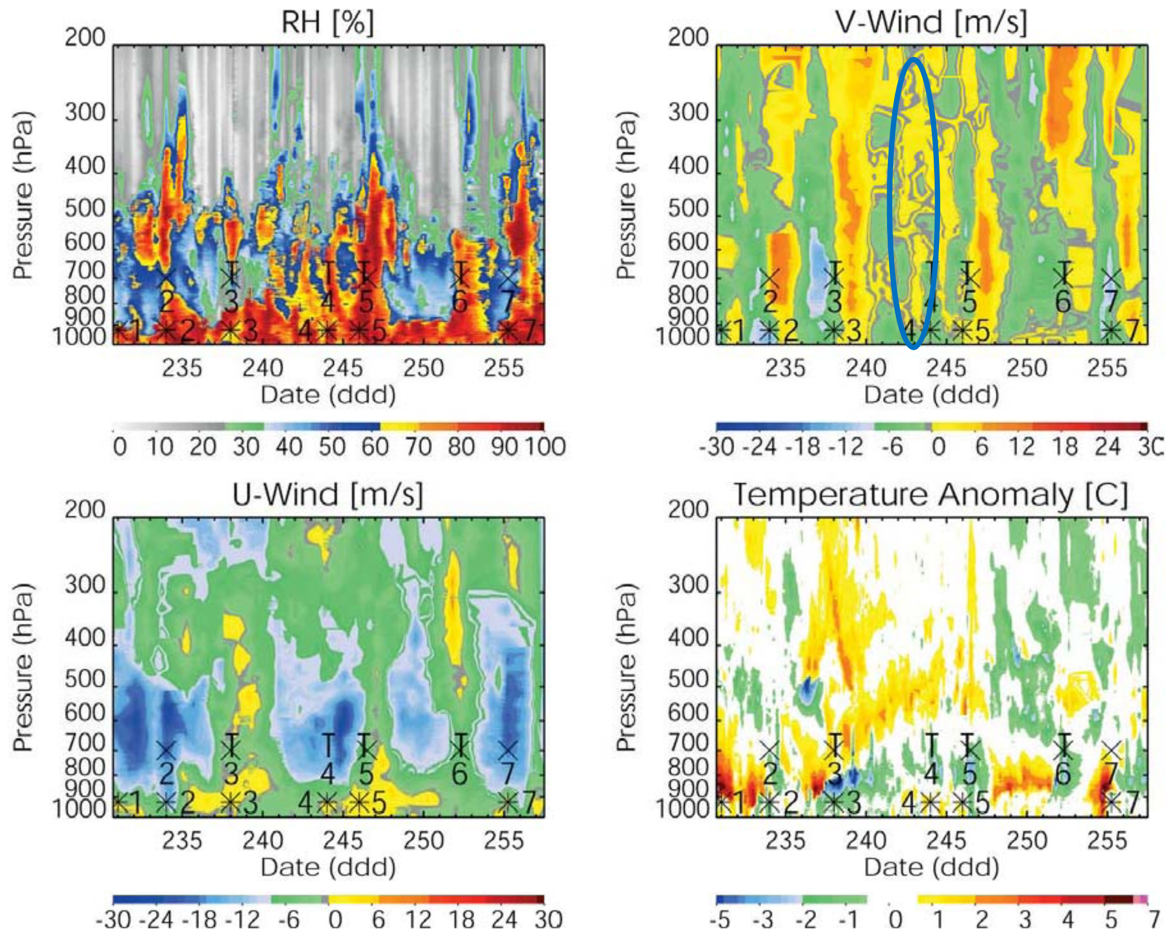


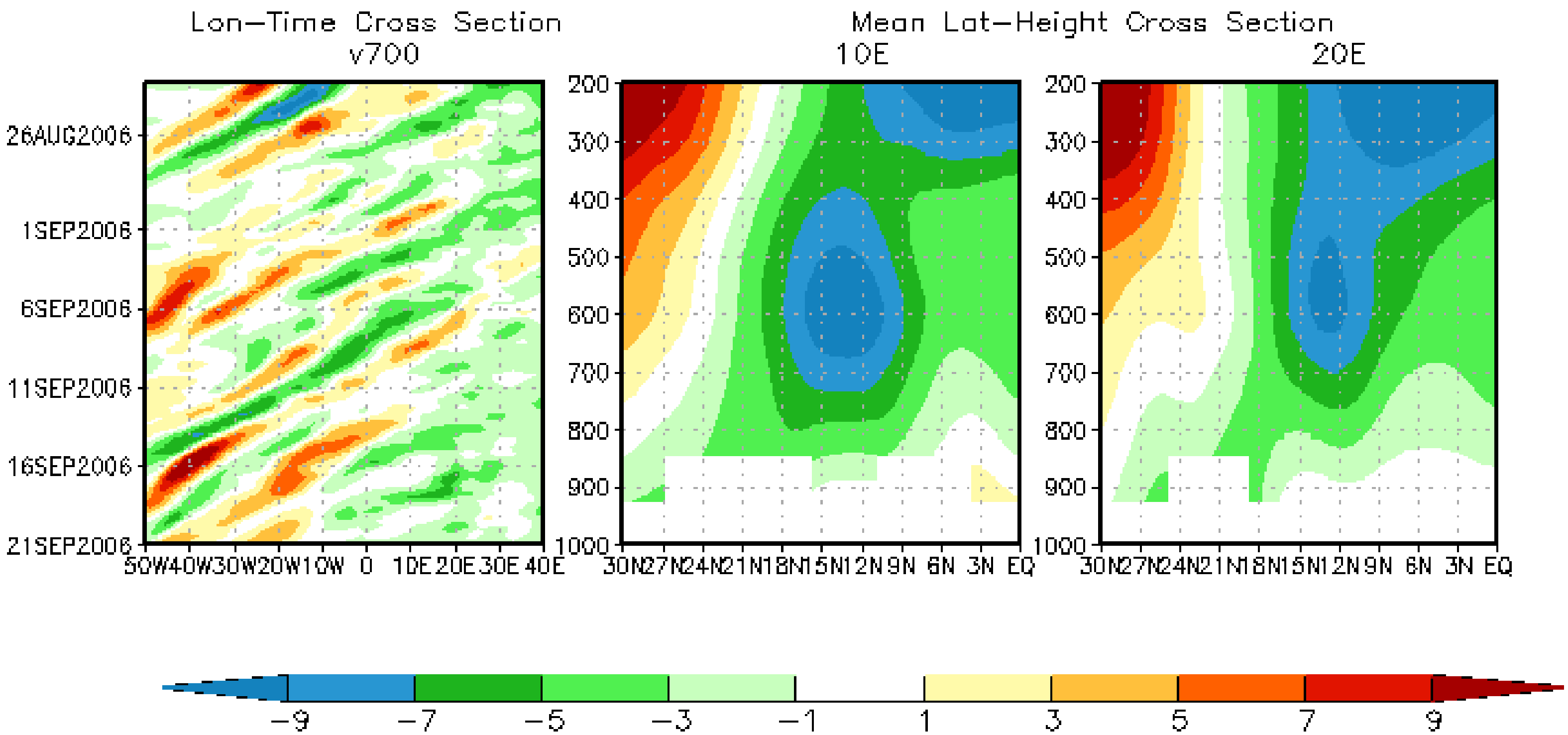
FIG. 2. Praia rawinsonde time series of (top left) RH, (top right) *V* wind, (bottom left) *U* wind, and (bottom right) temperature for the period between 1700 UTC 18 Aug (day 230) and 15 Sep 2006 (day 258). Here "X" indicates the passage time of an analyzed 700-hPa vorticity maximum, the "T" indicates the passage time of a 700-hPa wave trough, and the asterisk indicates the passage time of a 925-hPa vorticity maximum. Numbers indicate AEWs 1–7.

AEW 2 (pre-Debby)
AEW7 (pre-Helene),
Day 235 – Aug 23, 2006

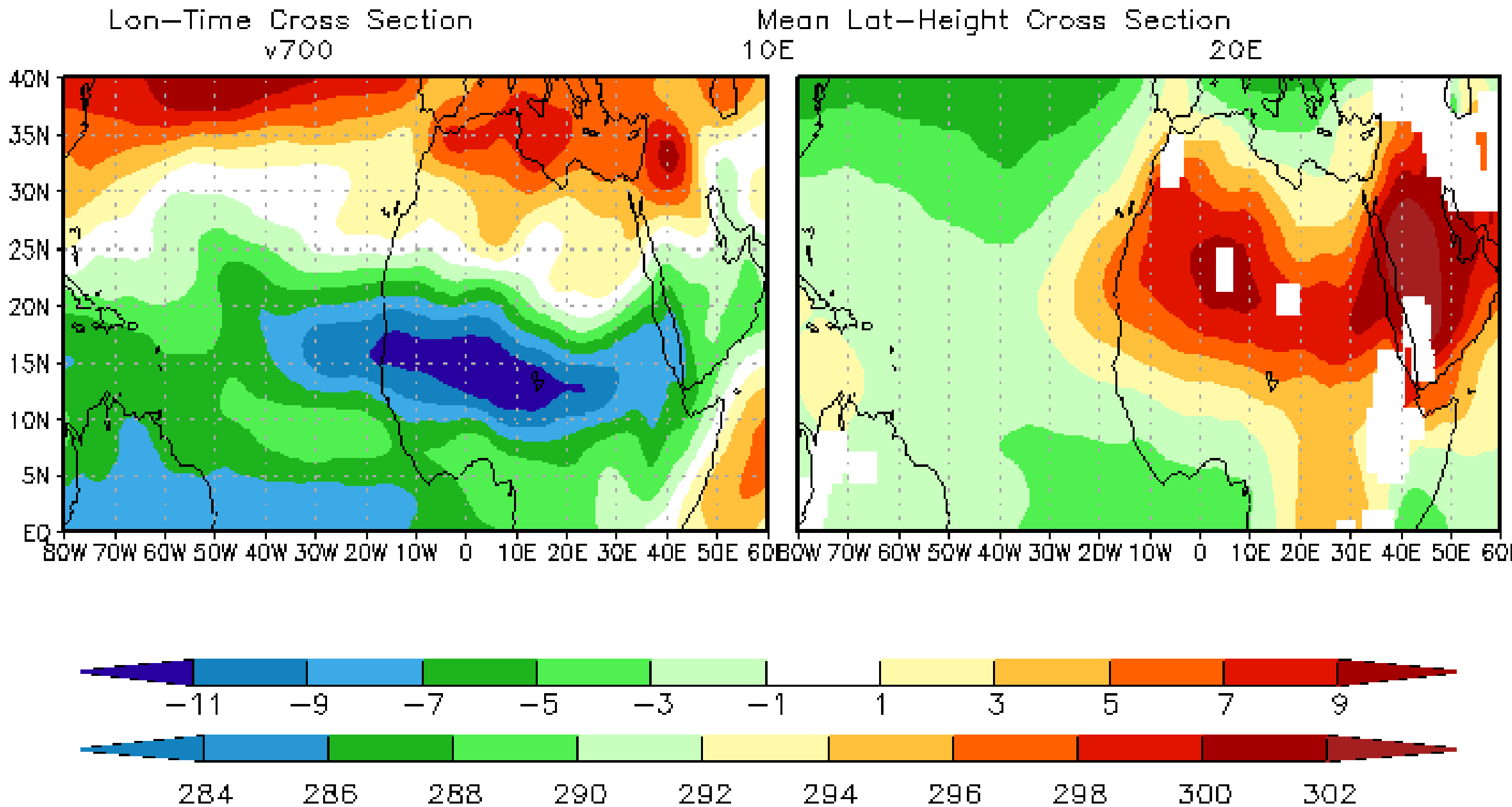
1) Neither is the V wind change highly correlated with other aspects of the height-time series, such as the enhancement of relative humidity or the zonal wind changes;
2) The temperature variations are included for completeness but are difficult to interpret
3) The aircraft missions are needed to add spatial detail

a) Wave AEW 1 is apparent by the meridional (V) wind change at low levels (~850-1000 hPa) but not at middlevels (above 800 hPa);
b) The opposite is true for wave AEW 6

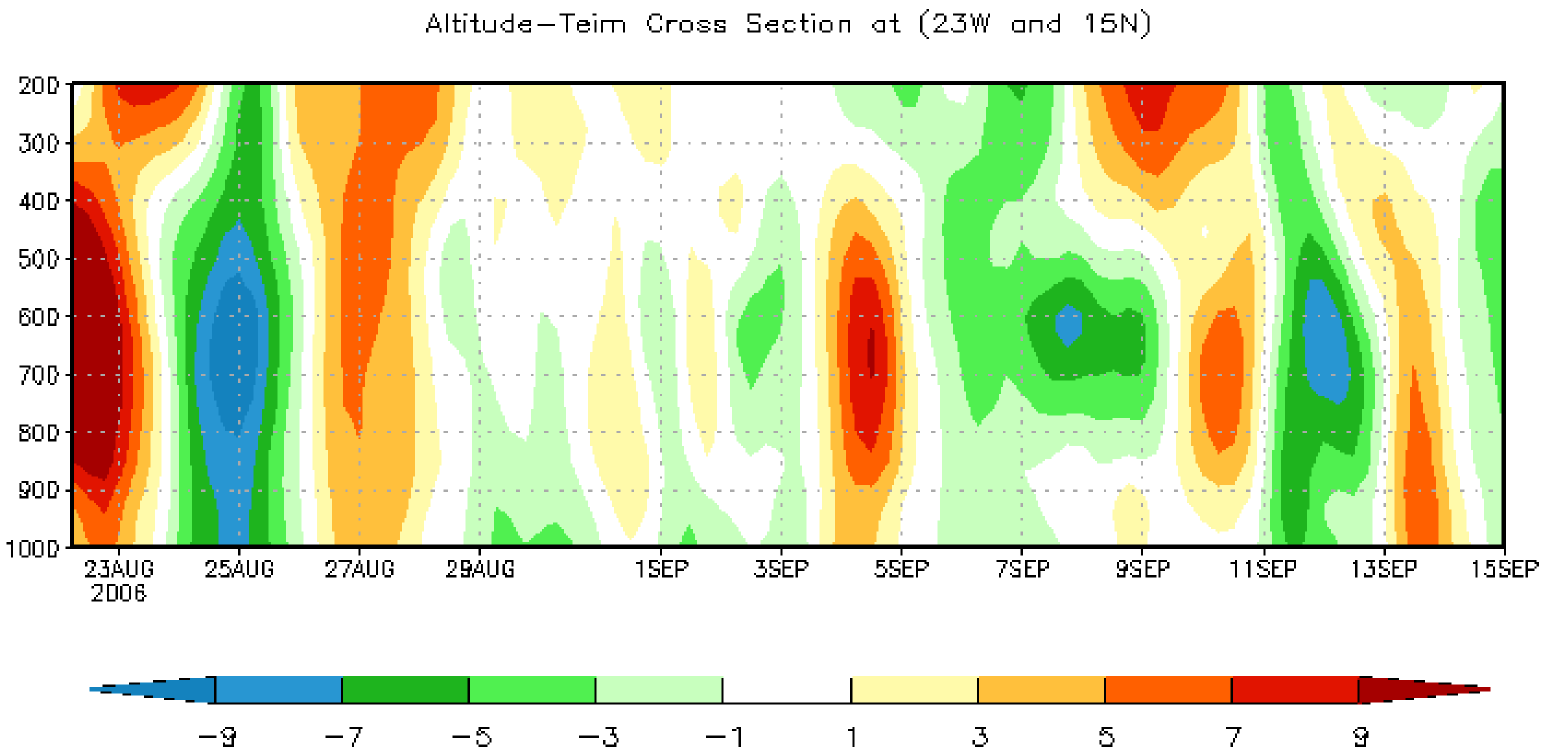
Different Analyses



Different Analyses



Different Analyses



Sensitivity Experiments

Case id	Dynamic IC	Clm and Physics IC	SST	Guinea Highlands	Remarks
cntl	08/22	08/22	weekly		
A	08/23	08/23	weekly		
B	08/24	08/24	weekly		Impact of initial "perturbations"
C	08/25	08/25	weekly		
D	08/22	Climate clm	weekly		
E	08/22	02/22	weekly		Impact of initial land surface conditions
F	08/22	08/22	climate		**Impact of SSTs**
G	04/22	04/22	weekly		Changed date to be 08/22/2006
H	06/22	06/22	weekly	**Impact of "physics"**	Changed date to be 08/22/2006
I	08/22	08/22	weekly	A factor of 0.6 in heights	**Impact of terrains**

Shen, B.-W. et al., 2010b: African Easterly Waves and African Easterly Jet in 30-day High-resolution Global Simulations. A Case Study during the 2006 NAMMA period. Geophys. Res. Lett., L18803, doi:10.1029/2010GL044355.

Sensitivity Experiments

Sensitivity to initial perturbations (e.g., AEJ)

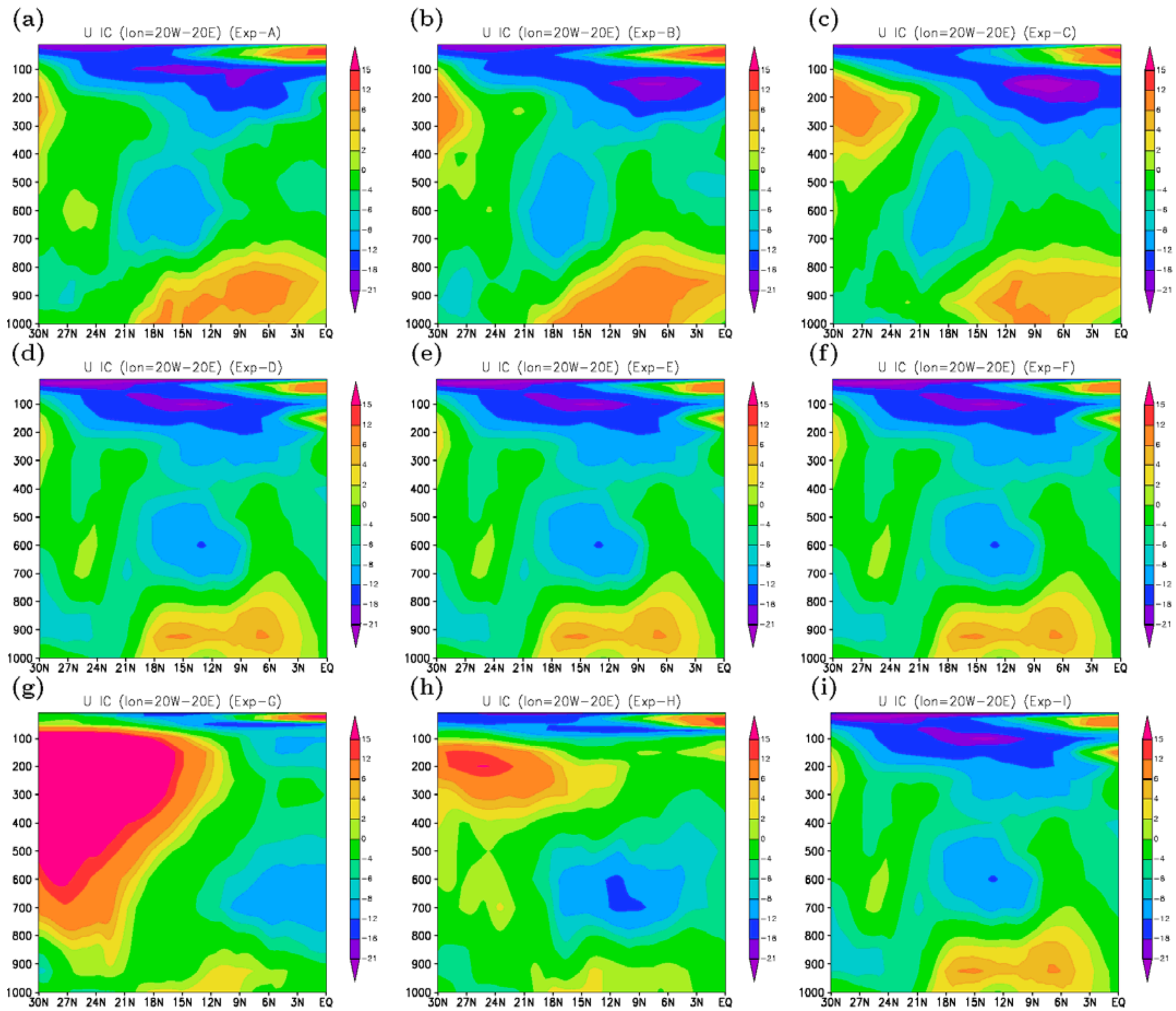
Sensitivity to initial land surface conditions

Sensitivity to surface sea temperatures (SSTs) → oceanic feedbacks on AEW simulations; (impact on large-scale flows in the upstream; subsequent atmosphere-land interactions; initiation of AEWs; intensification of the 4^{th} AEW; formation of the model 'Helene'

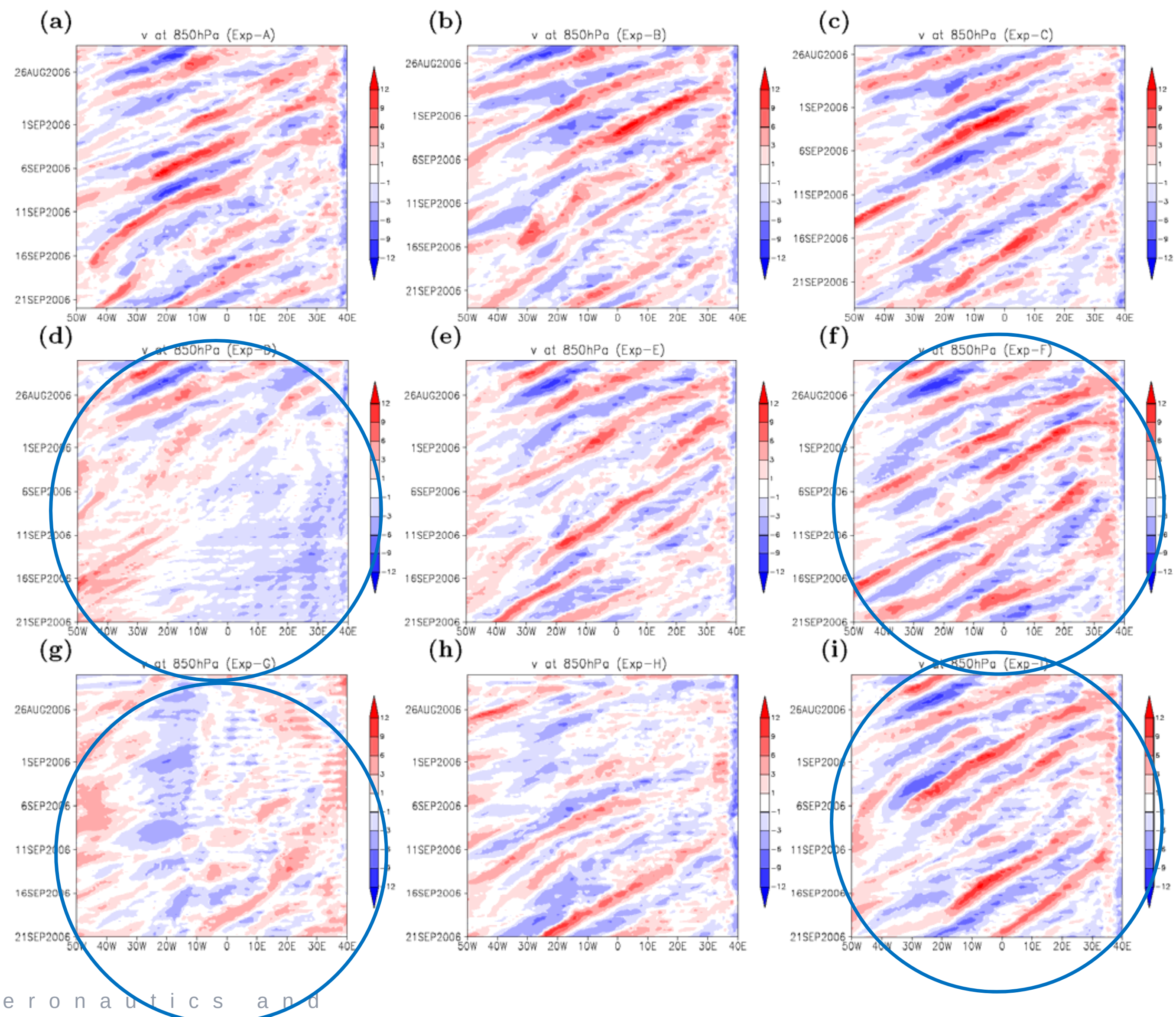
Sensitivity to physics (with realistic land surface conditions)

Impact of a reduced mountain height on the simulations of upstream flows

Initial Zonal Winds

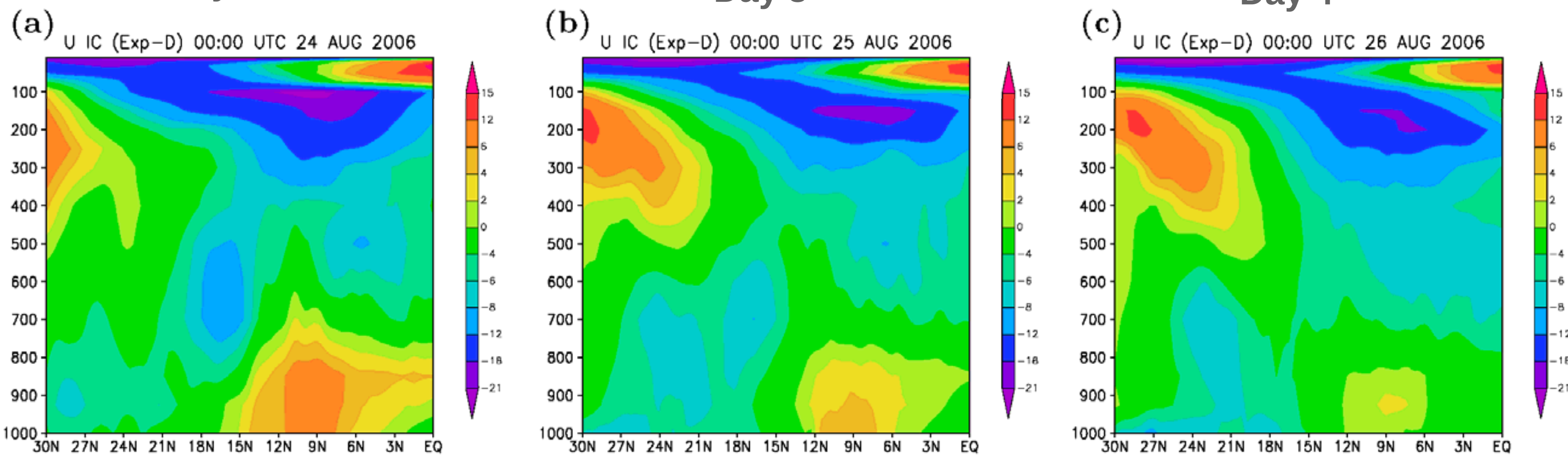


Sensitivity Experiments



Experiment D: AEJ Dissipation

Day 2 Day 3 Day 4

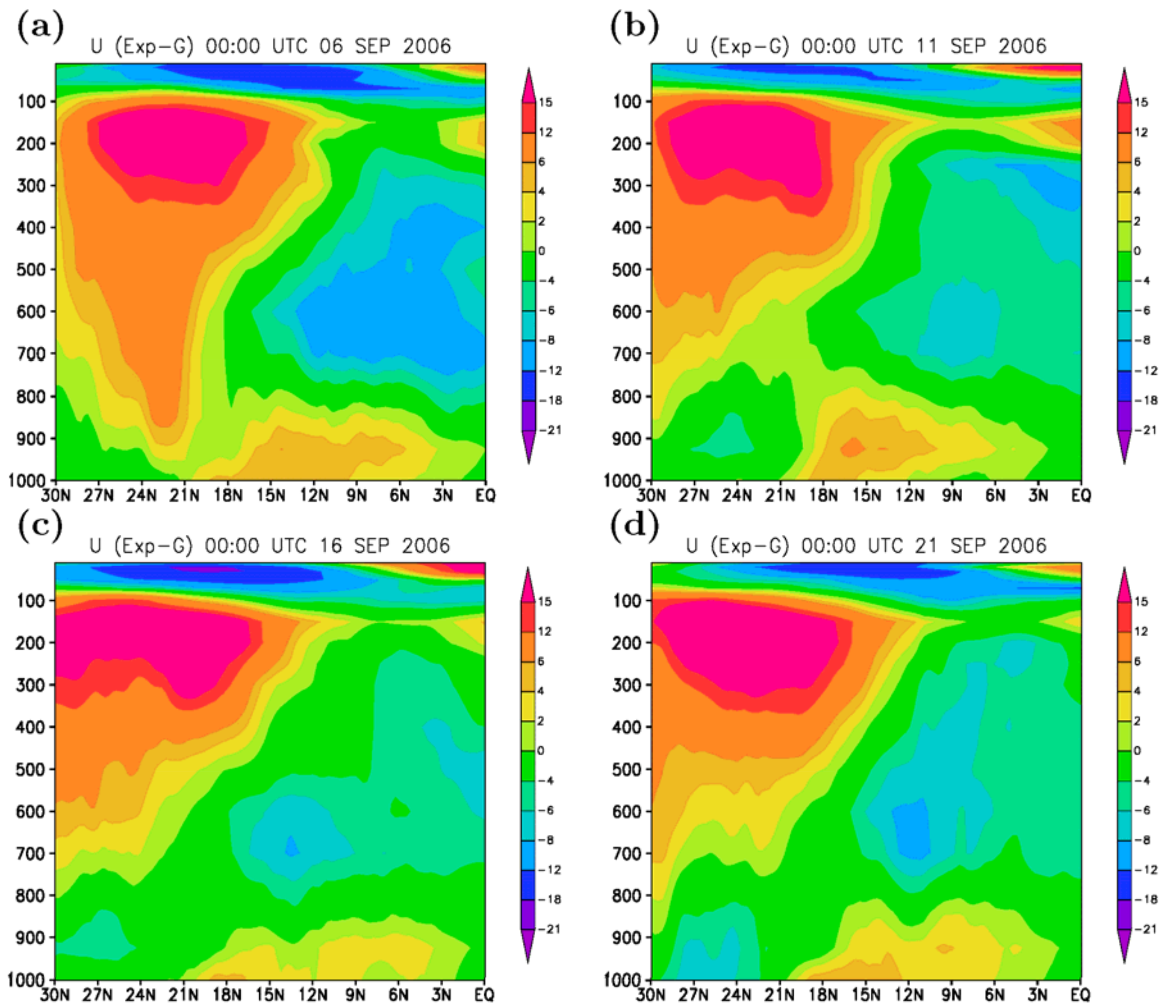


30^{o}N Latitude EQ

Experiment G: AEJ development

Day 15

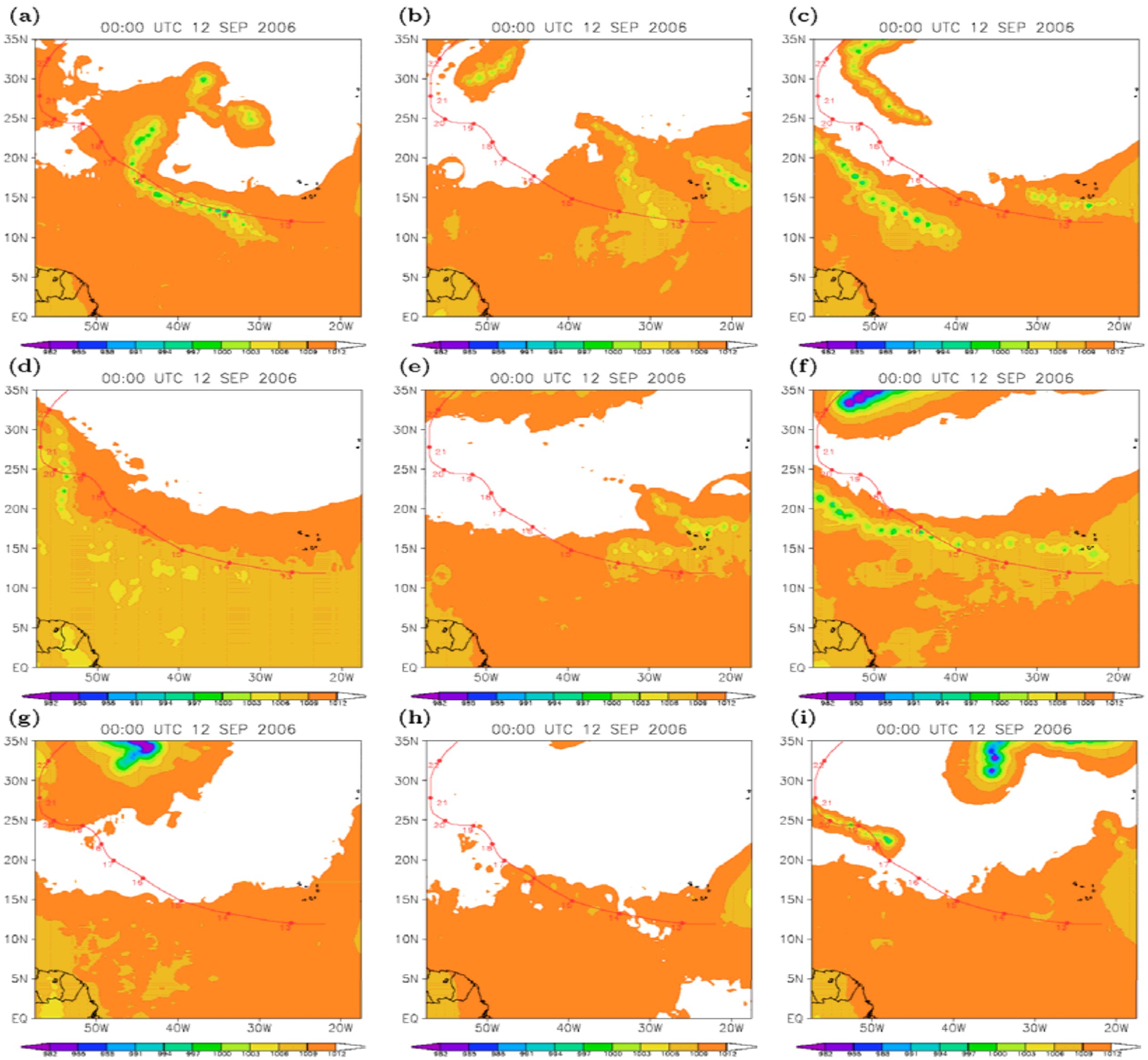
Day 20



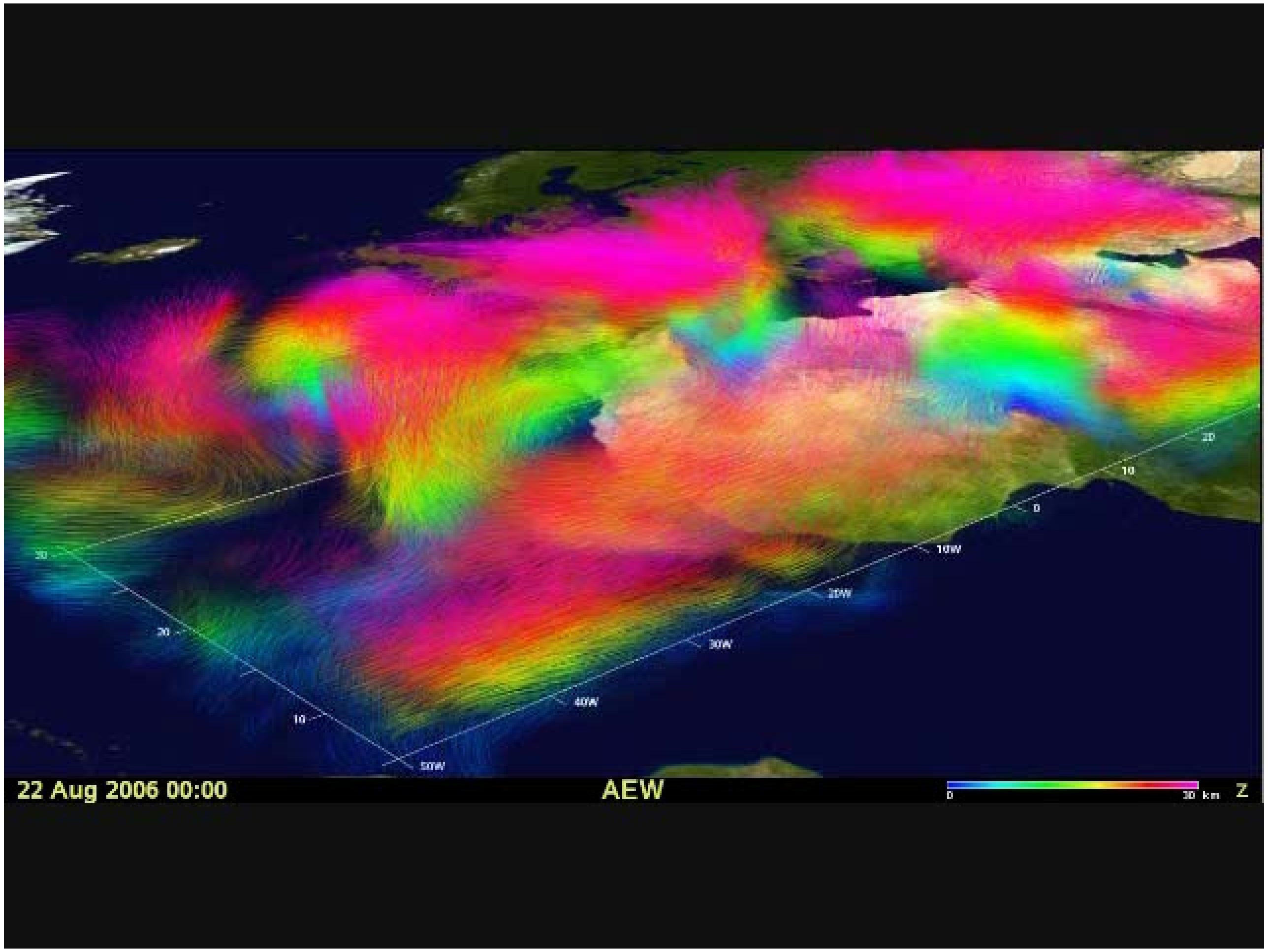
Day 25

Day 30

Sensitivity of Helene Simulations



Visualizations of AEWs and Hurricanes



Summary

- To expend the lead time of hurricane formation, we investigate the multiscale interactions of the African easterly waves (AEWs) and AEJ
- The statistical characteristics of individual 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.
- While land surface processes may contribute to the predictability of the AEJ and AEWs (as a BVP), 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 IVP).
- 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.
- In the experiment with climate SSTs, differences appear in the 5^{th} and 6^{th} AEWs and shows that the effects of using climatological SSTs on the simulation of AEW initiation begin to occur after 15-20 days of integration
- The reduced height of guinea highlands caused significant differences in the simulations of AEWs since at 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.