Monsoon Dynamics and Computational Modeling Techniques

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UNIVERSITY OF NOTRE DAME
College of Science

Outline

Impact of Indian Monsoon on Society

- Long history of inaccurate forecasts[6].
  - Incorrect forecasts cause speculation.
- Monsoon rains intrinsically impact Indian, and global, economy[3].
  - Normal monsoon - 96-104% of 89cm 50-year average each season.
  - Below 90% = drought.
  - Vital for agriculture sector - 15% of $2 trillion econonmy.
  - Monsoon boosts market demand and can mitigate inflation.
- Climate Disasters
  - 2015 - Chennai Floods
  - 2016 - Drought and Mass Migration[1]
- Better Prediction = less speculation and more resiliency

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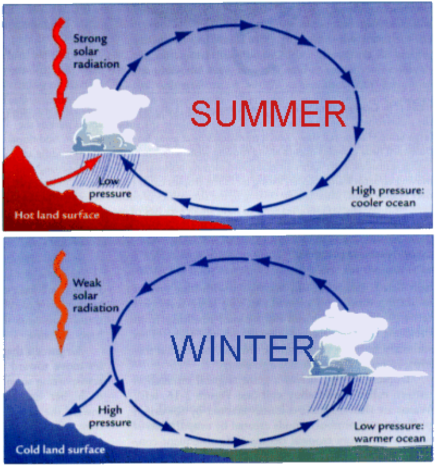
Monsoon Dynamics



Historically, Halley (1686) attributed monsoons to heating contrast between land and ocean, i.e. an enormous sea-breeze[4].

However, this description does not account for certain monsoon features, like delayed onset or the active-break cycle.

Standard Numerical Weather Prediction models (NWP is based on Navier-Stokes equations) require additional multiphysics dynamics to fully capture the monsoon system.

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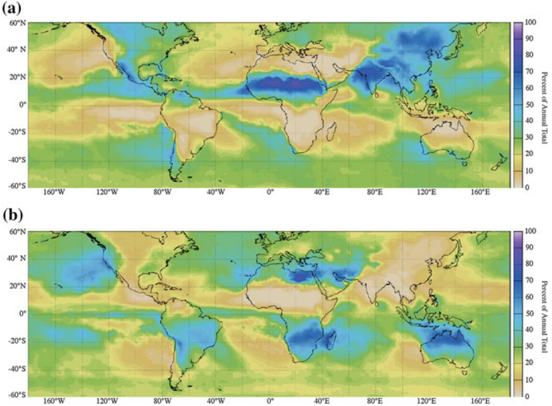

Top: Boreal Summer   Bottom: Boreal Winter

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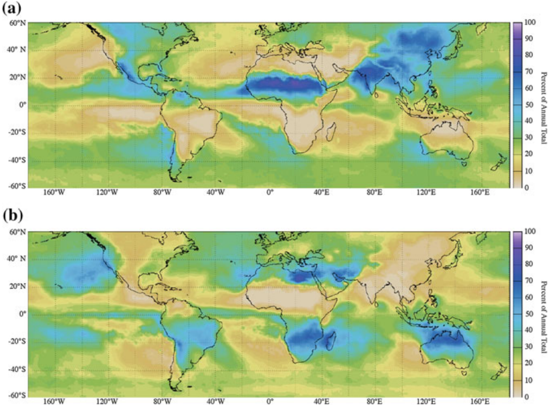

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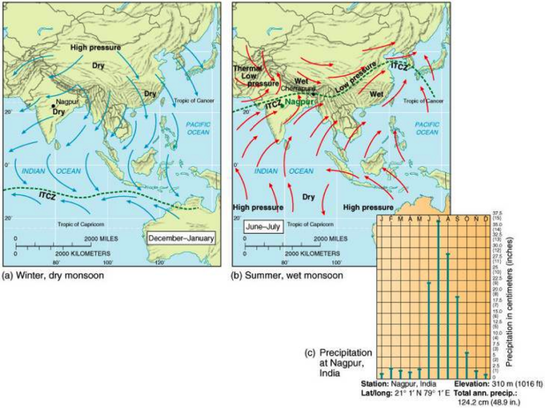

The Climate of Tropical Regions. URL: http://thebritishgeographer.weebly.com/the-climate-of-tropical-regions.html

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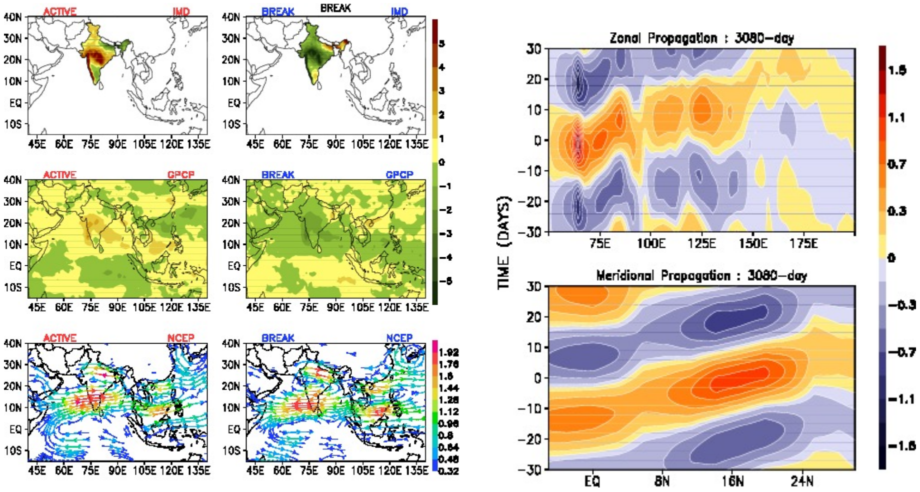
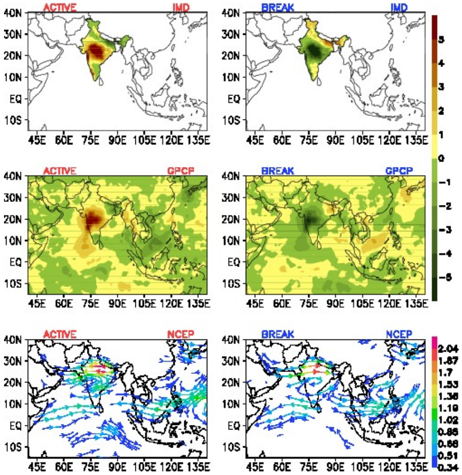
Break Cycles and Monsoon IntraSeasonal Oscillations

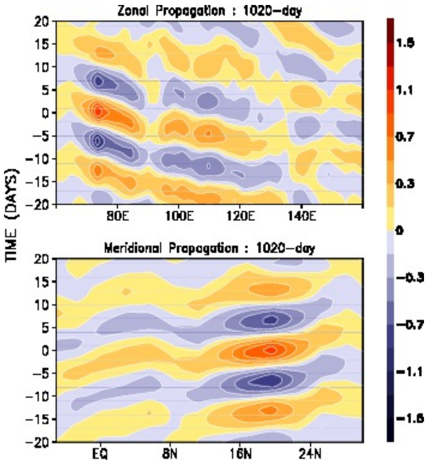
Low Frequency MISO (30-60 Day) - Northward propogating



Break Cycles and Monsoon IntraSeasonal Oscillations

High Frequency MISO (10-20 Day) - Westward propogating





Compressible Euler Equations

Performing NWP involves solving Navier-Stokes equations, simplified as the Euler Equations:

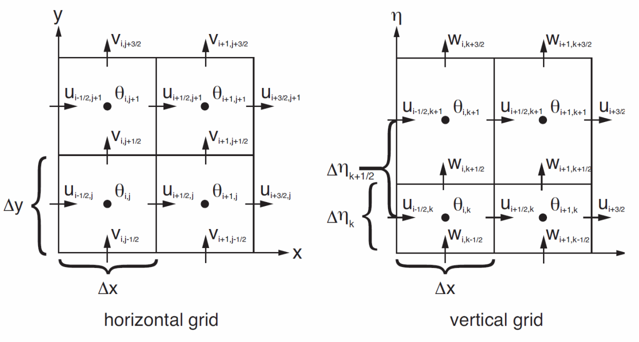
$$
\begin{aligned}
\partial_t U + (\nabla \cdot \mathbf{V} u) - \partial_x(p\phi_\eta) + \partial_\eta(p\phi_x) &= F_U \\
\partial_t V + (\nabla \cdot \mathbf{V} v) - \partial_y(p\phi_\eta) + \partial_\eta(p\phi_y) &= F_V \\
\partial_t W + (\nabla \cdot \mathbf{V} w) - g(\partial_\eta p - \mu) &= F_W \\
\partial_t \Theta + (\nabla \cdot \mathbf{V} \theta) &= F_\Theta \\
\partial_t \mu + (\nabla \cdot \mathbf{V}) &= 0 \\
\partial_t \phi + \mu^{-1}[(\mathbf{V} \cdot \nabla \phi) - gW] &= 0
\end{aligned}
$$

This tracks momentum in 3D, potential temperature conversation, mass conservation, and geopotential respectively.

$F_\star$ terms represent forcings from model physics, turbelent mixing, spherical projections, Coriolis forces, etc. In WRF, options select physics suites and orders of accuracy.

Compressible Euler Equations

The Weather and Research Forecasting (WRF) model solves the Euler governing equations in separate horizontal and vertical domains via a Finite Volume solver using explicit Finite Difference approximations.



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$$\psi_i^{t+\Delta t} - \psi_i^t = -\frac{\Delta t}{\Delta x}\left(flux_{i+1/2} - flux_{i-1/2}\right)$$

ψ_{i-3}	ψ_{i-2}	ψ_{i-1}	ψ_i	ψ_{i+1}	ψ_{i+2}

$$for\ U_{i-1/2} \geq 0$$

$$flux_{i-1/2} = U_{i-1/2}\left(\frac{w_0}{\overline{w}} f_0 + \frac{w_1}{\overline{w}} f_1 + \frac{w_2}{\overline{w}} f_2\right)$$

$$where\ \overline{w} = w_0 + w_1 + w_2$$

$$f_0 = \frac{1}{3}\psi_{i-3} - \frac{7}{6}\psi_{i-2} + \frac{11}{6}\psi_{i-1} \qquad w_0 = \frac{0.1}{(\varepsilon + \beta_0)^2}$$

$$f_1 = -\frac{1}{6}\psi_{i-2} + \frac{5}{6}\psi_{i-1} + \frac{1}{3}\psi_i \qquad w_1 = \frac{0.6}{(\varepsilon + \beta_1)^2}$$

$$f_2 = \frac{1}{3}\psi_{i-1} + \frac{5}{6}\psi_i - \frac{1}{6}\psi_{i+1} \qquad w_2 = \frac{0.3}{(\varepsilon + \beta_2)^2}$$

$$\beta_0 = \frac{13}{12}\left(\psi_{i-3} - 2\psi_{i-2} + \psi_{i-1}\right)^2 + \frac{1}{4}\left(\psi_{i-3} - 4\psi_{i-2} + 3\psi_{i-1}\right)^2$$

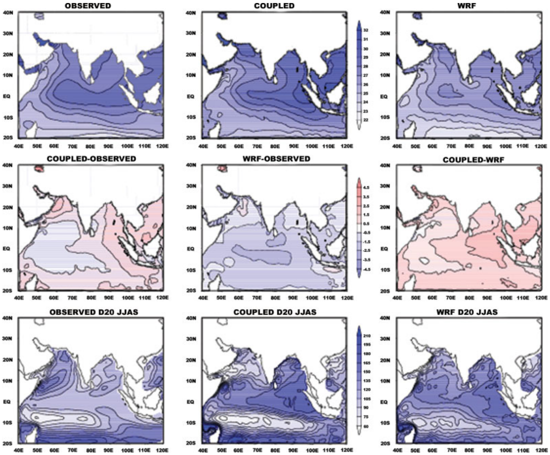
$$\beta_1 = \frac{13}{12}\left(\psi_{i-2} - 2\psi_{i-1} + \psi_i\right)^2 + \frac{1}{4}\left(\psi_{i-2} - 4\psi_{i-1} + 3\psi_i\right)^2$$

$$\beta_2 = \frac{13}{12}\left(\psi_{i-1} - 2\psi_i + \psi_{i+1}\right)^2 + \frac{1}{4}\left(\psi_{i-1} - 4\psi_i + 3\psi_{i+1}\right)^2$$

= 5 : 5th order PD WENO

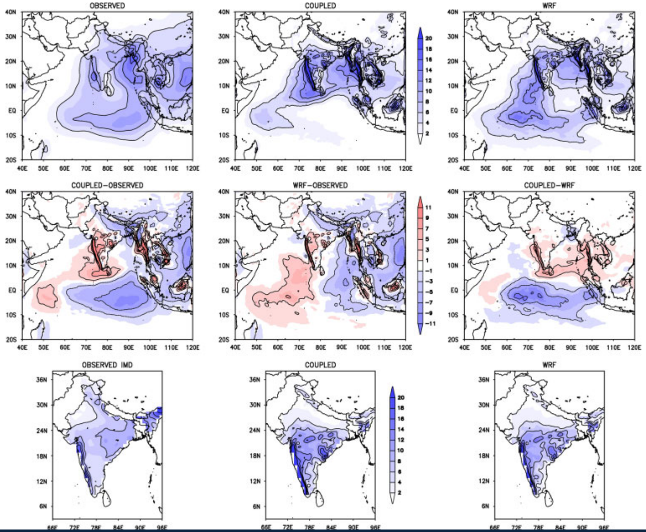
Weighted Essentially Non-Oscillatorry (WENO) schemes comprise flux formulations

WRF alone poorly models ISM. So we seek to couple to an ocean model. Sea Surface Temperatures and D20 isotherm depths are shown below.



Air-Sea Coupling

Averaged rainfall Jun-Jul-Aug-Sep are shown where surface wind stress, net energy fluxes, and SST are exchanged in coupled model (Samala).

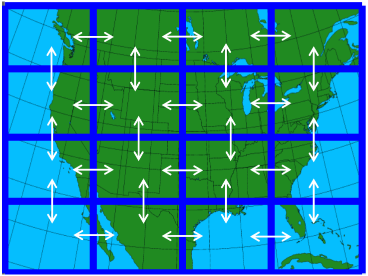


NWP and Communication Overhead

WRF simulations can take days to run depending on parameters, so speedup is crucial!

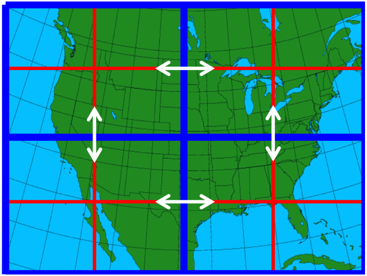
MPI Only

Excessive halo communication



Hybrid with OpenMP

Less overhead



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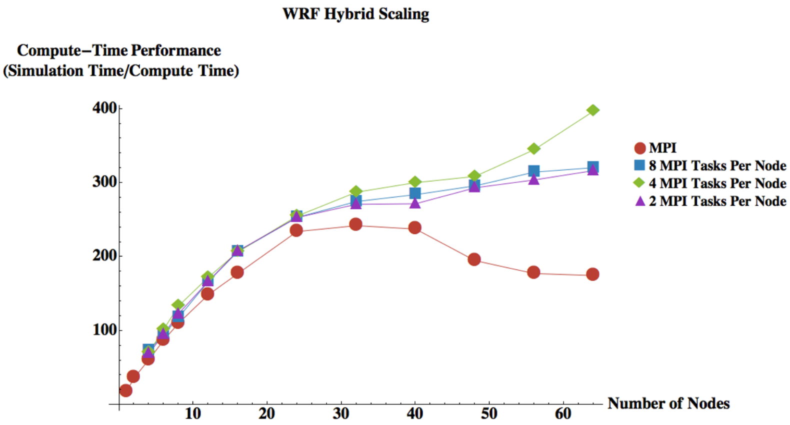
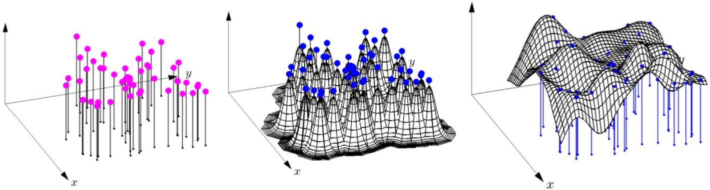


Samm Elliott. *WRF Performance Optimization Targeting Intel Multicore and Manycore Architectures*. Apr. 2017

Formulation and Benefits of RBF-FD Methods

RBF-FD Generates weights in scattered node FD formulas

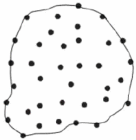
- Total geometric flexibility
- No connexctivities or mappings are required
- Excellent for distributed memory computation
- Easy to achieve high order accuracy
- Local node refinement trivial



Formulation and Benefits of RBF-FD Methods

RBF is formulated as a linear combination in a radial basis:

Scattered nodes:



Interpolant: $s(\underline{x}) = \sum_{k=1}^{N} \lambda_k \Psi_k(\underline{x})$

System that determines the expansion coefficients λ

$$\begin{bmatrix} \Psi_1(\underline{x}_1) & \Psi_2(\underline{x}_1) & \cdots & \Psi_N(\underline{x}_1) \\ \Psi_1(\underline{x}_2) & \Psi_2(\underline{x}_2) & \cdots & \Psi_N(\underline{x}_2) \\ \vdots & \vdots & & \vdots \\ \Psi_1(\underline{x}_N) & \Psi_2(\underline{x}_N) & \cdots & \Psi_N(\underline{x}_N) \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_N \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_N \end{bmatrix}$$

The interpolant is then defined given properties of matrix row swaps:

$$s(\underline{x}) = \sum_{k=1}^{n} \lambda_k \phi(\| \underline{x} - \underline{x}_k \|)$$

Solve system A x = $\underline{f}$, of the form:

$$\begin{bmatrix} \phi(\| \underline{x}_1 - \underline{x}_1 \|) & \phi(\| \underline{x}_1 - \underline{x}_2 \|) & \cdots & \phi(\| \underline{x}_1 - \underline{x}_n \|) \\ \phi(\| \underline{x}_2 - \underline{x}_1 \|) & \phi(\| \underline{x}_2 - \underline{x}_2 \|) & \cdots & \phi(\| \underline{x}_2 - \underline{x}_n \|) \\ \vdots & \vdots & \ddots & \vdots \\ \phi(\| \underline{x}_n - \underline{x}_1 \|) & \phi(\| \underline{x}_n - \underline{x}_2 \|) & \cdots & \phi(\| \underline{x}_n - \underline{x}_n \|) \end{bmatrix} \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \vdots \\ \lambda_n \end{bmatrix} = \begin{bmatrix} f_1 \\ f_2 \\ \vdots \\ f_n \end{bmatrix}$$

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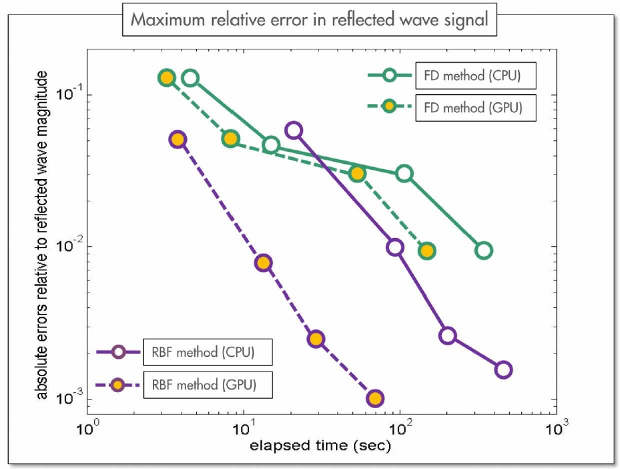

Summary

Important Takeaways

- MISO dynamics are internal to monsoon system and hard to predict.
- Effective and efficient air-sea coupling models need to be employed for good simulation results of monsoons.
- Novel algorithms are key to greatest improvements in speed so long as HPC design is made a priority.

Future Work

- Identify key dynamics of MISO generation for models to address.
- Implement air-sea coupled solvers, including salinity structure to better capture ocean heat content distribution.
- Further investigate DG and RBF-FD Methods for feasibility in NWP and given time, utility in WRF.
- Perform data validation on MISO simulations and compare which models capture MISO signals best.

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Thank you! - Questions?

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