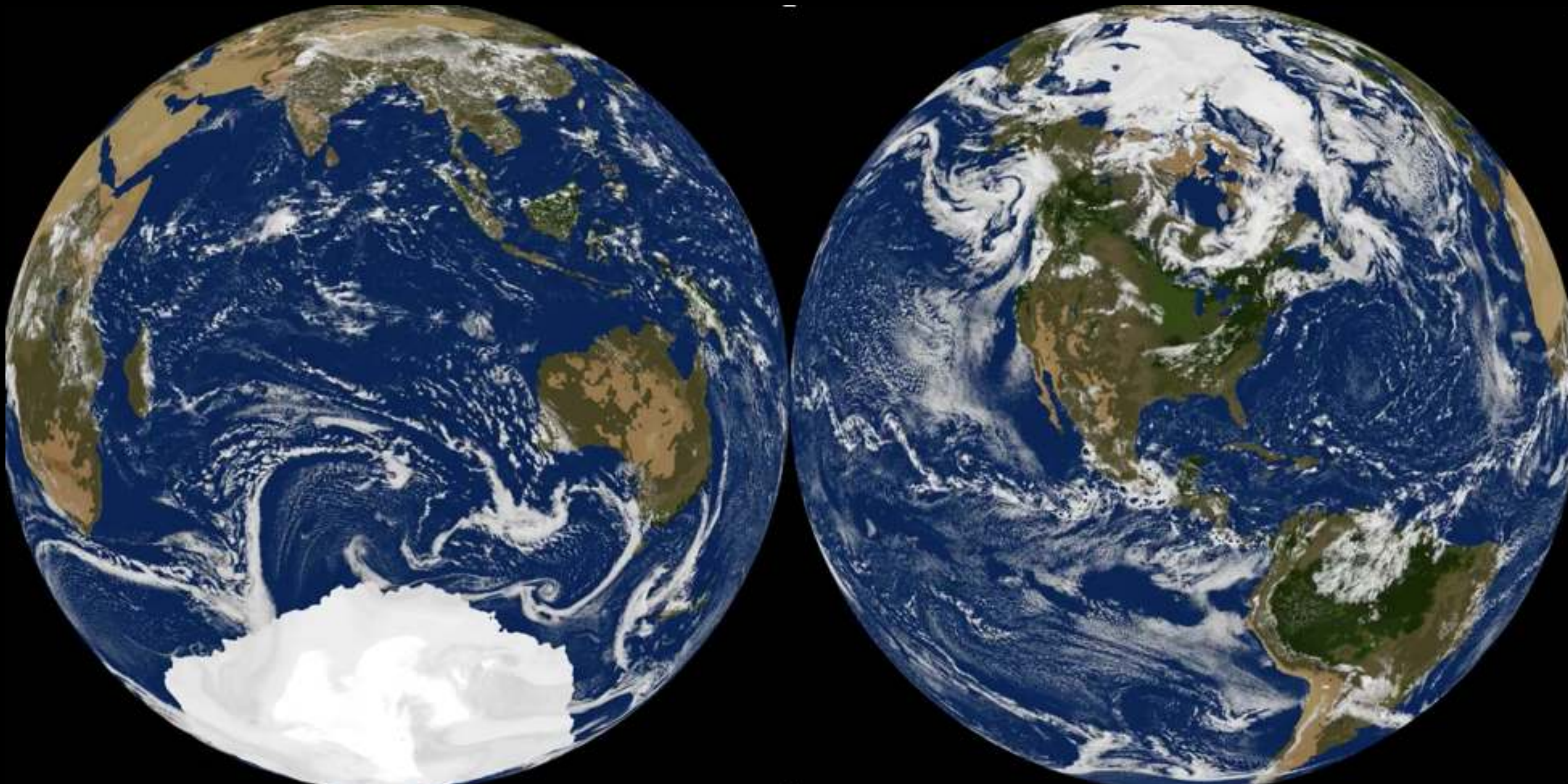
Global SAM

Marat Khairoutdinov



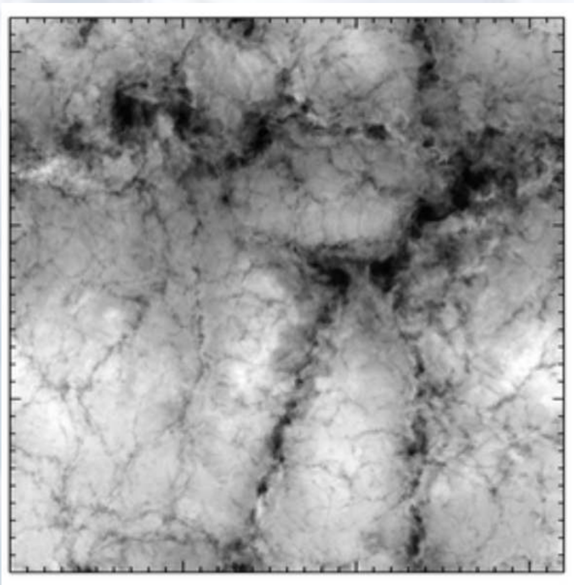
Stony Brook University
Long Island, New York, USA

DYAMOND Workshop, Mainz, Germany June 19–20, 2019

SAM: System for Atmospheric Modeling

Cloud-Resolving Model (CRM) / Large-Eddy Simulation (LES) Model

- Has been around since late 90s
- Anelastic (no sound waves), non-hydrostatic; 2D or 3D;
- Smagorinski 1st order or 1.5 prognostic TKE SGS closure;
- Radiation packages: NCAR CAM3 and RRTM;
- 2nd-order space and 3rd-order Adams-Bashforth time differences for momentum;
- Conservation of momentum and kinetic energy;
- fully 3-D positive definite and monotonic transport (MPDATA) for all scalars;
- Several cloud microphysics packages of various complexity;
- Comprehensive land-surface model with different types of vegetation and interactive soil
- "Box-fill" method for the topography;
- Massively parallel (domain decomposition, MPI);



Spherical coordinates (Lat-Lon grid) : φ - latitude, μ=cos(φ)

x = rλ, y=rφ, where r is Earth radius.

Cartesian grid when μ=1 (r=oo)

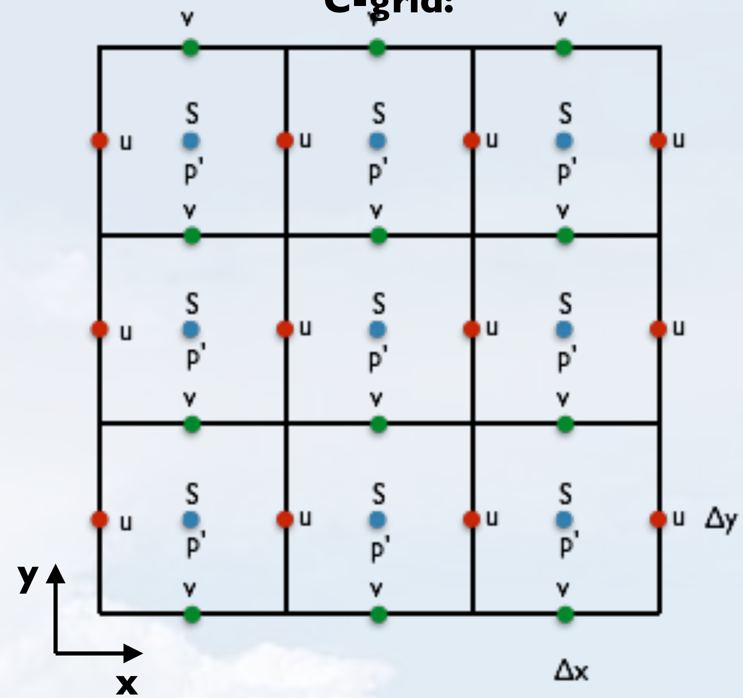
Momentum (anelastic approximation, no sound waves):

$$\frac{\partial u}{\partial t}+\frac{1}{\mu}\frac{\partial}{\partial x}uu+\frac{1}{\mu\rho_0}\frac{\partial}{\partial y}\mu\rho_0 uv+\frac{1}{\rho_0}\frac{\partial}{\partial z}\rho_0 uw=-\frac{1}{\mu}\frac{\partial\pi}{\partial x}+\left(f+\frac{u}{r}\tan\varphi\right)v+Du$$

$$\frac{\partial v}{\partial t}+\frac{1}{\mu}\frac{\partial}{\partial x}vu+\frac{1}{\mu\rho_0}\frac{\partial}{\partial y}\mu\rho_0 vv+\frac{1}{\rho_0}\frac{\partial}{\partial z}\rho_0 vw=-\frac{\partial\pi}{\partial y}-\left(f+\frac{u}{r}\tan\varphi\right)u+Dv$$

$$\frac{\partial w}{\partial t}+\frac{1}{\mu}\frac{\partial}{\partial x}wu+\frac{1}{\mu\rho_0}\frac{\partial}{\partial y}\mu\rho_0 wv+\frac{1}{\rho_0}\frac{\partial}{\partial z}\rho_0 ww=-\frac{\partial\pi}{\partial z}+B+Dw$$

C-grid:



Continuity:

$$\frac{1}{\mu}\frac{\partial}{\partial x}u+\frac{1}{\mu\rho_o}\frac{\partial}{\partial y}\mu\rho_o v+\frac{1}{\rho_o}\frac{\partial}{\partial z}\rho_o w=0$$

Scalars :

$$\frac{\partial S}{\partial t}+\frac{1}{\mu}\frac{\partial}{\partial x}wS+\frac{1}{\mu}\frac{\partial}{\partial y}\mu vS+\frac{1}{\rho_0}\frac{\partial}{\partial z}\rho_0 wS=Q+Dw$$

SGS Diffusion:

$$D\psi=\frac{1}{\mu^2}\frac{\partial}{\partial x}k_h\frac{\partial\psi}{\partial x}+\frac{1}{\mu\rho_o}\frac{\partial}{\partial y}\mu k_h\frac{\partial\psi}{\partial y}+\frac{1}{\rho_o}\frac{\partial}{\partial z}\rho_o k_z\frac{\partial\psi}{\partial z}$$

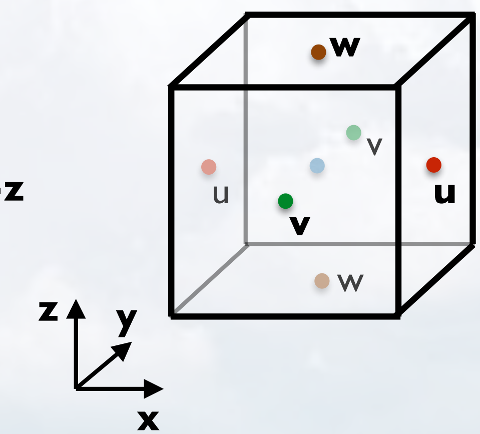
Still same horizontal grid with constant Δx and Δy

Single Reference State profiles:

$$\rho_o=\rho_o(z)$$

$$T_o=T_o(z)$$

Pressure Solver:
FFT in x, multigrid in y-z



Diagnostic Equation for Pressure p'

Cartesian grid

Poisson equation:

$$\frac{\partial^2 p'}{\partial x^2} + \frac{\partial^2 p'}{\partial y^2} + \frac{\partial}{\partial z}\bar{\rho}\frac{\partial}{\partial z}\frac{p'}{\bar{\rho}} = F$$

3-D elliptic equation
on Cartesian grid

Fourier transformation in x and y (FFT):

$$p' = \sum_{mn} \hat{p}_{mn} e^{i(mx+ny)} \qquad F = \sum_{mn} \hat{F}_{mn} e^{i(mx+ny)}$$

Works when Δx and Δy are constant

Diagnostic equation for Fourier coefficients:

$$-(m^2 + n^2)\hat{p}_{mn} + \frac{1}{\bar{\rho}}\frac{\partial}{\partial z}\bar{\rho}\frac{\partial \hat{p}_{mn}}{\partial z} = \hat{F}_{mn}$$

1-D equation - easy! ($N_x N_y$ of them)

Diagnostic Equation for Pressure p'

Lat-Lon Grid

Lat-Lon grid - Poisson equation:

$$\frac{\partial^2 p'}{\partial x^2} + \mu \frac{\partial}{\partial y} \mu \frac{\partial p'}{\partial y} + \mu^2 \frac{\partial}{\partial z} \bar{\rho} \frac{\partial}{\partial z} \frac{p'}{\bar{\rho}} = F\mu^2$$

Remember: $\mu = \mu(y)$

Fourier transformation in x only (FFT):

$$p' = \sum_m \hat{p}_m e^{imx} \qquad F = \sum_m \hat{F}_m e^{imx}$$

Δx is constant, but coefficients μ are functions of y - can't use FFT in y as in Cartesian!

Need to solve 2-D Helmholtz (Poisson for m=0) equation with Neumann boundary conditions:

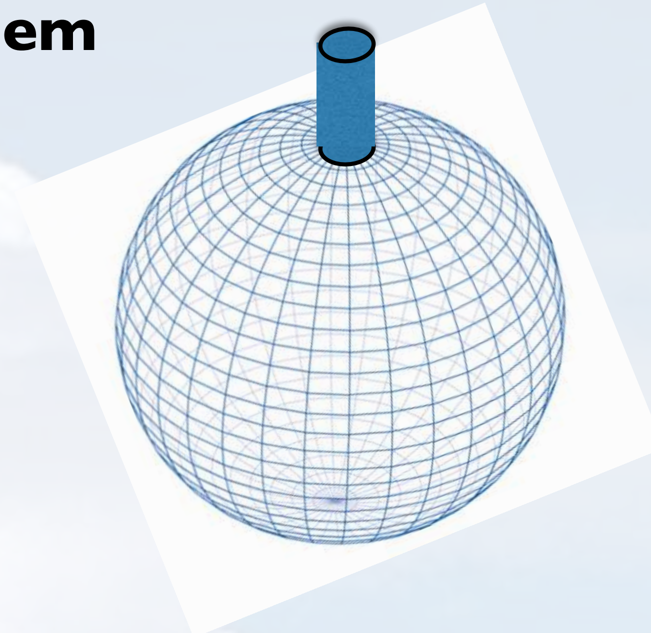
$$-m^2 \hat{p}_m + \mu \frac{\partial}{\partial y} \mu \frac{\partial \hat{p}_m}{\partial y} + \mu^2 \frac{\partial}{\partial z} \bar{\rho} \frac{\partial}{\partial z} \frac{\hat{p}_m}{\bar{\rho}} = \hat{F}_m \mu^2$$

2-D (y-z) equation (N_x of them)

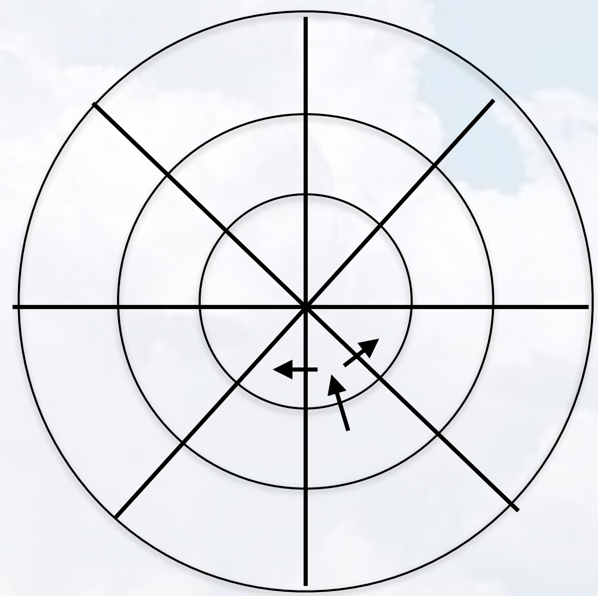
Solution: Custom made Geometric Multi-Grid (GMG) solver for Highly Anisotropic and Singular Elliptic problems with Neumann BCs

Typical convergence is a single V-Cycle even in the presence of hurricanes!

Pole Problem



**Used for DYAMOND run:
a wall around the pole at
89ºN-S.**

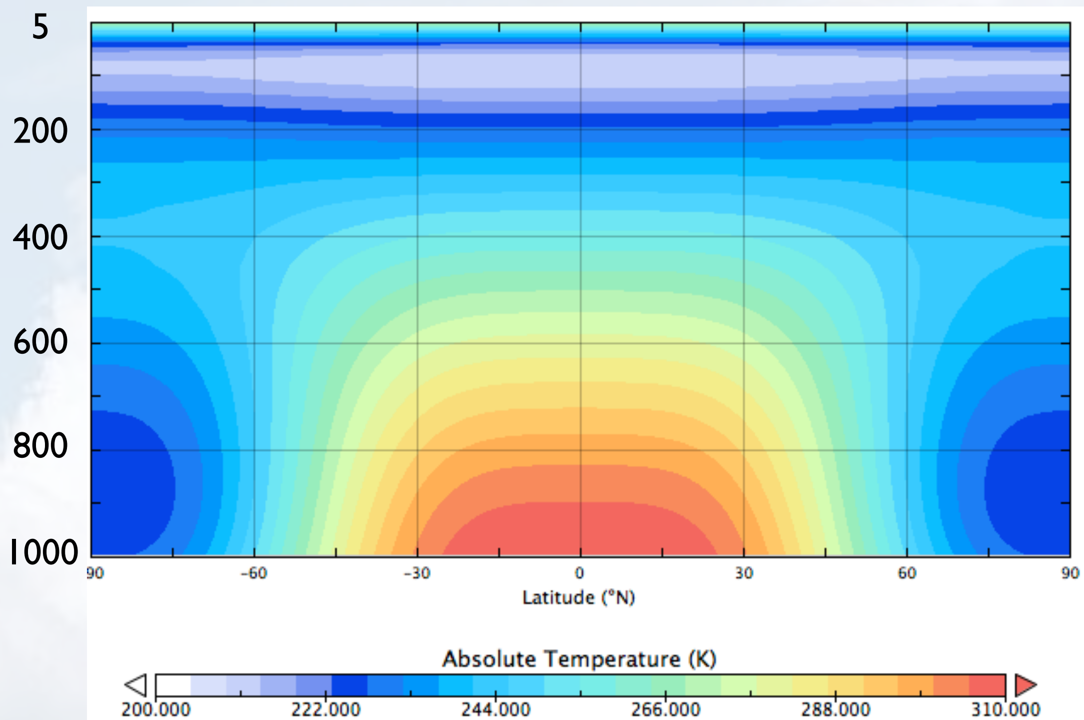


**Current:
Triangular grid cells at the pole;
Algebraic grid coarsening**

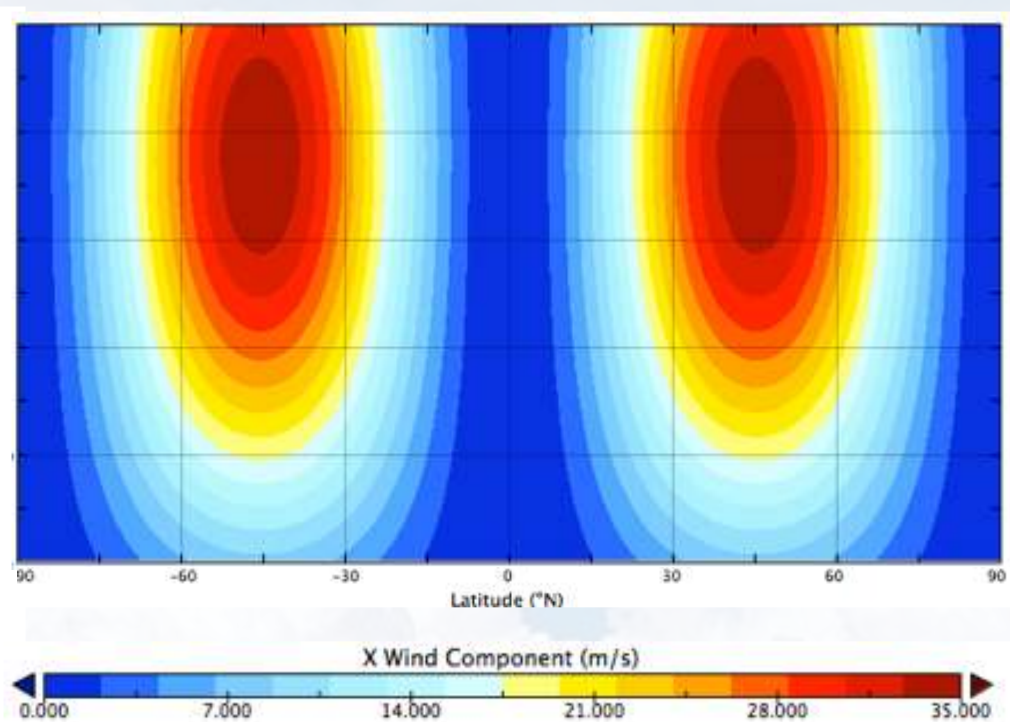
How adequate is the anelastic approximation, in particular, a single reference profile, for a global model?

Dry baroclinic-wave test (Jablonowski and Williamson 2006)

Prescribed Temperature



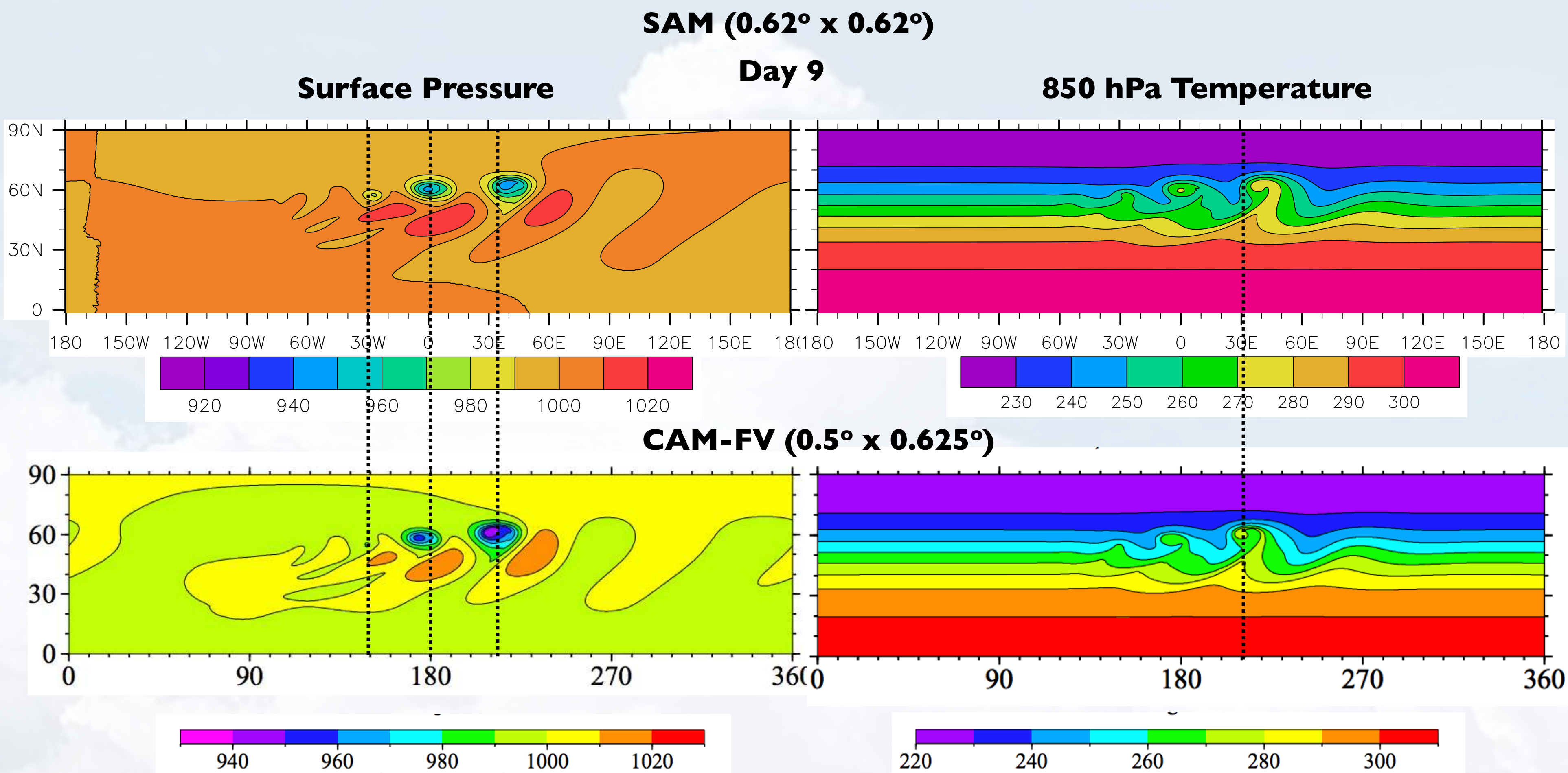
Exact Thermal Wind solution



Setup:

- **578x288x74 grid; 0.62 x 0.62 degrees**
- **Single reference profiles as a global mean profiles of T and ρ;**
- **Initial conditions: u from analytical solution, v=0;**
- **No friction, no SGS viscosity, no damping;**
- **Reference profiles are the global mean profiles;**
- **Run for 30 days;**

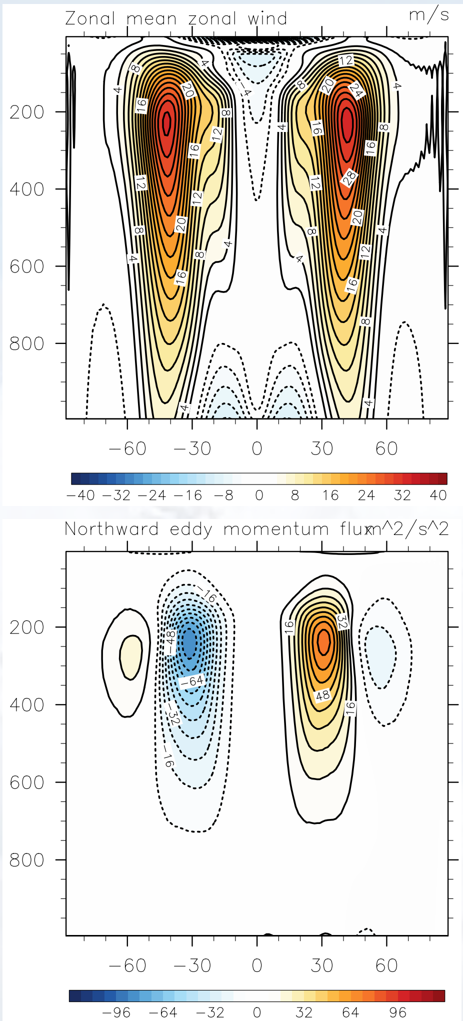
Dry Baroclinic Wave Test (Jablonowski and Williamson 2006)



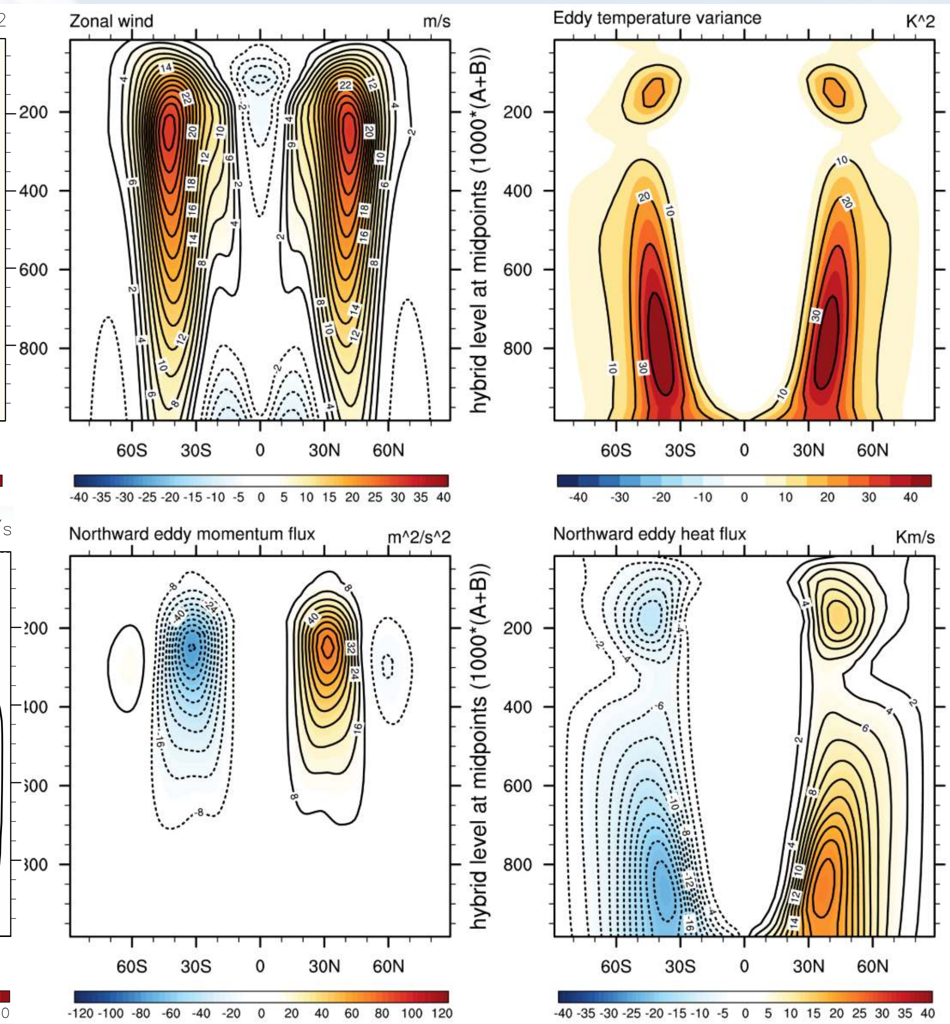
Problem: SAM's baroclinic wave propagation is a bit faster than in other global models

Held-Suarez Dry DyCore Test

SAM (0.6º x 0.6º)



CAM-EUL (T85)



Held-Suarez Dry DyCore Test

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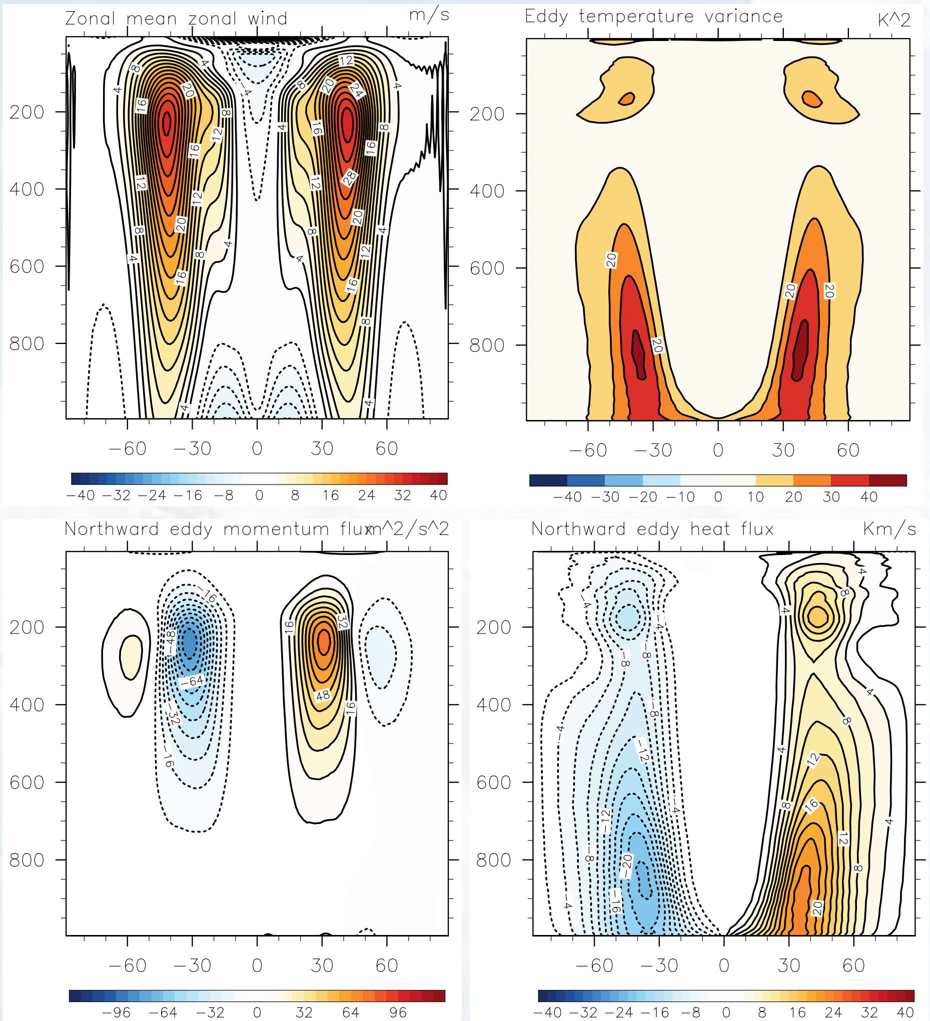
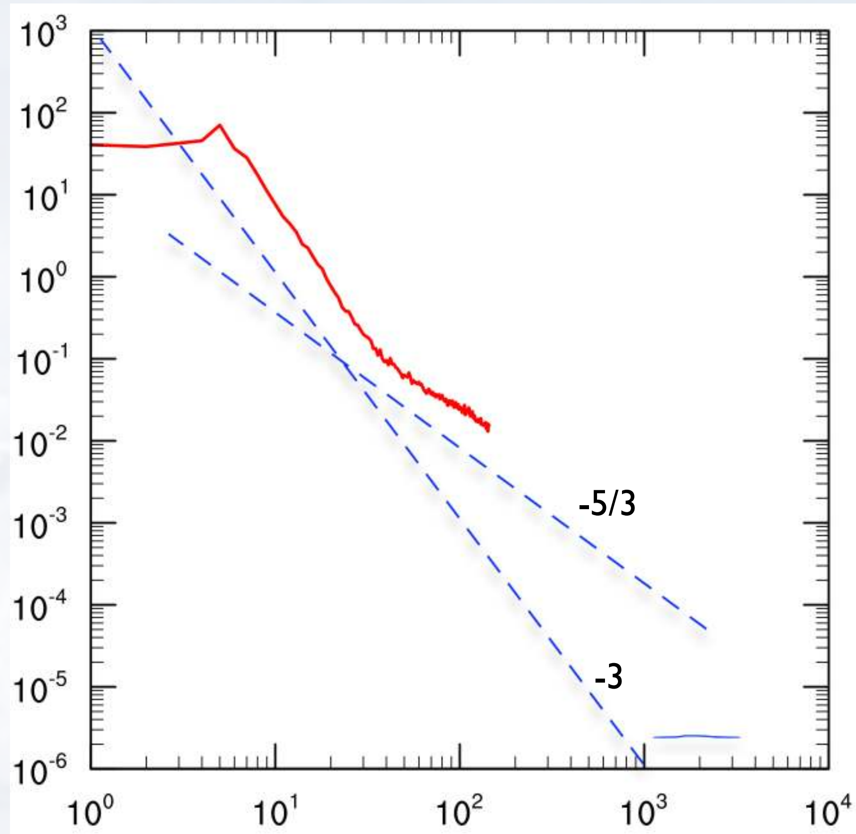
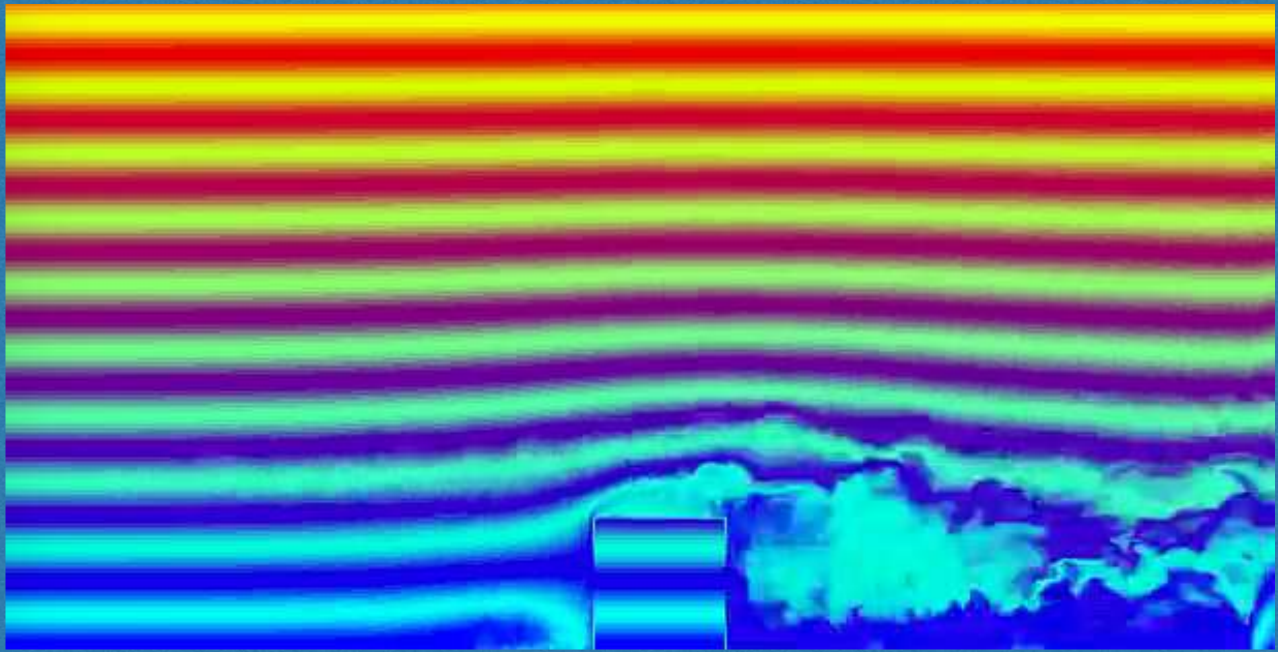
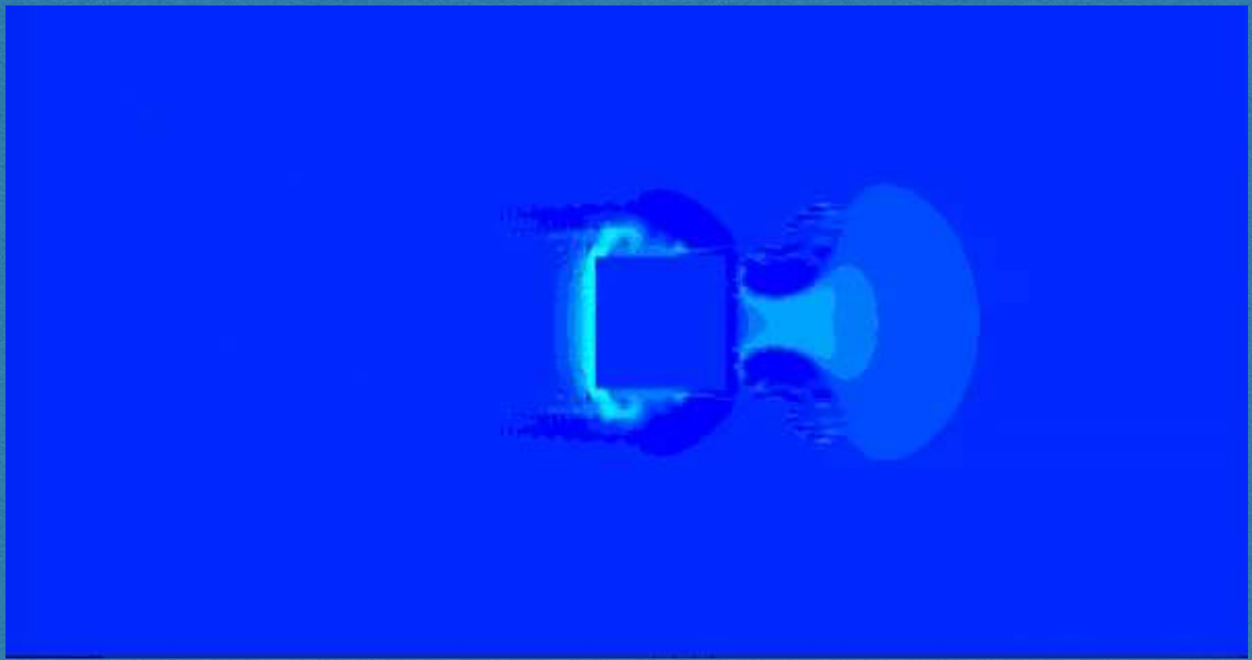


Zonal velocity spectrum mid-latitudes

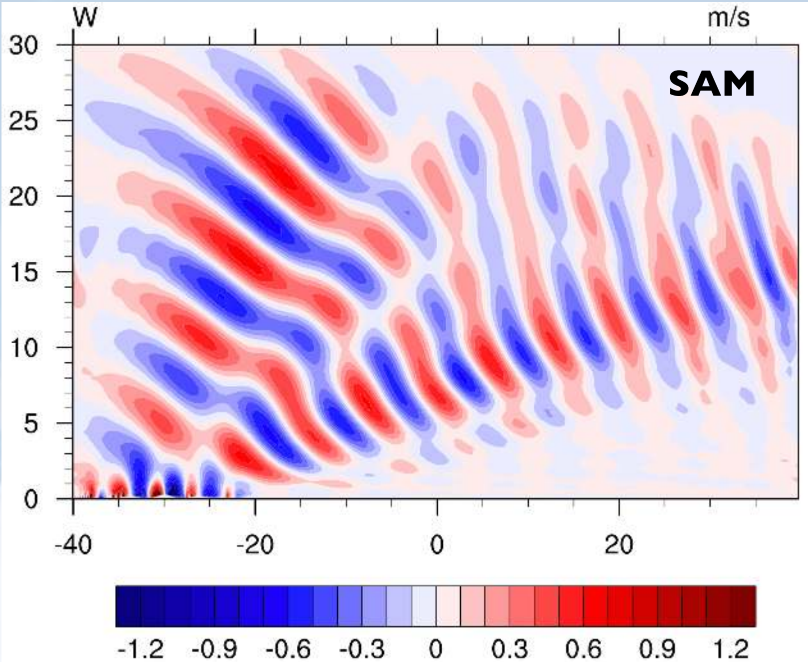


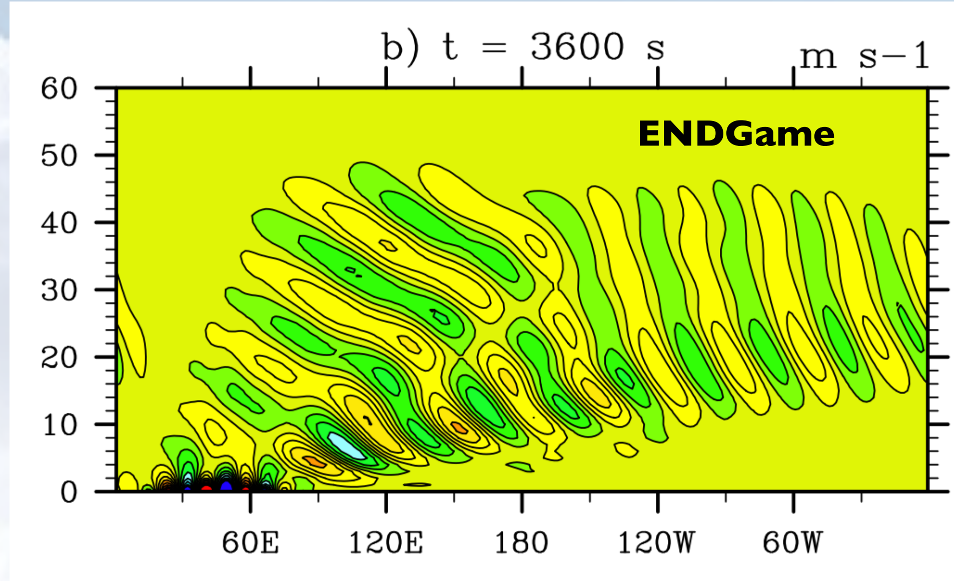
Simulation of a cube in wind tunnel
"Fill-box" method

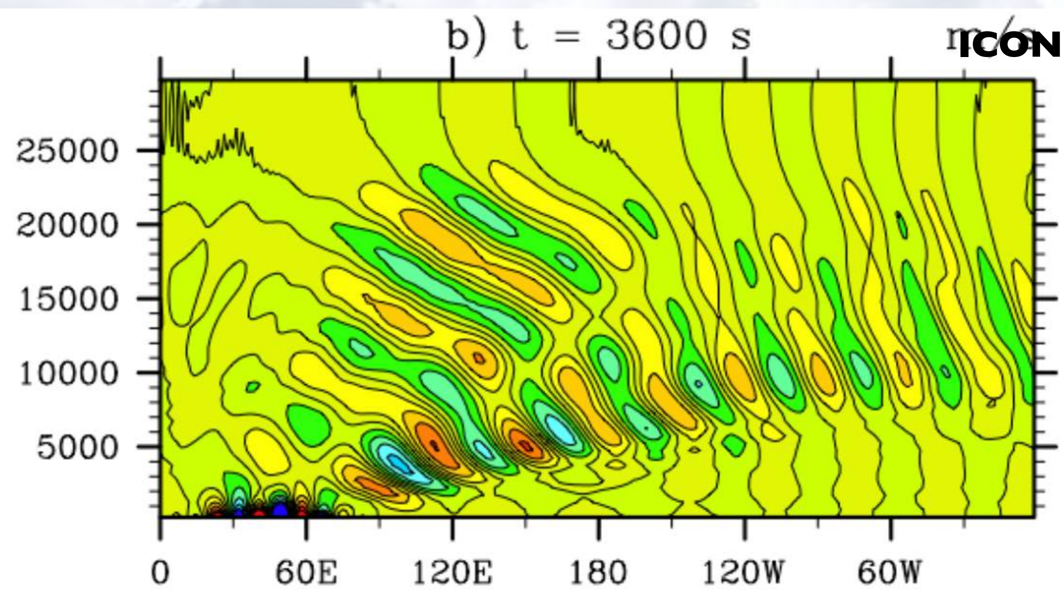


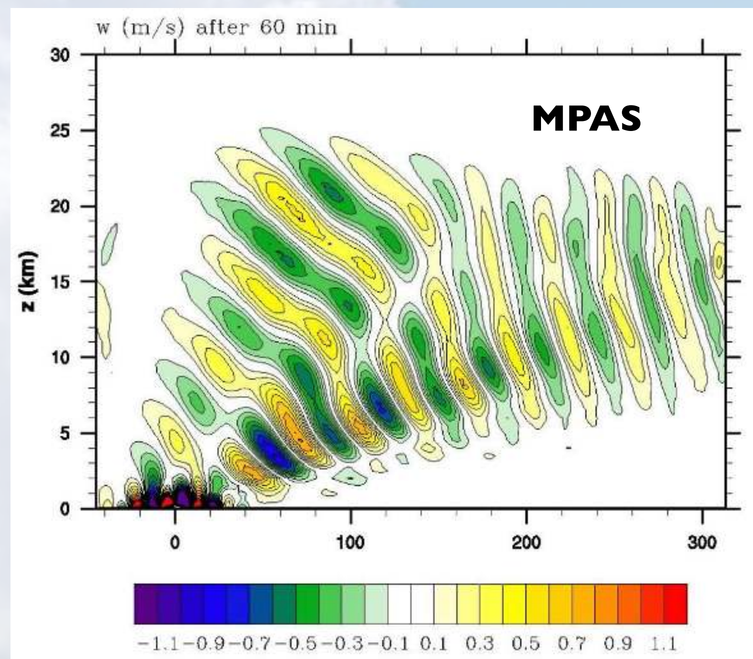


DCMIP 2.1 case: Mountain waves over a Schaer-type mountain on a small planet without shear (X=500): 80 levels, only 5 levels below mountain top at 250m





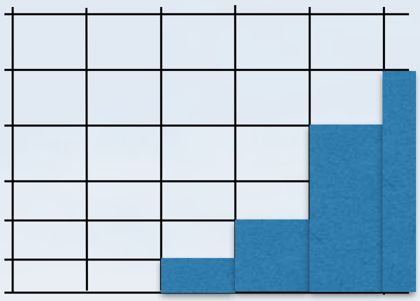




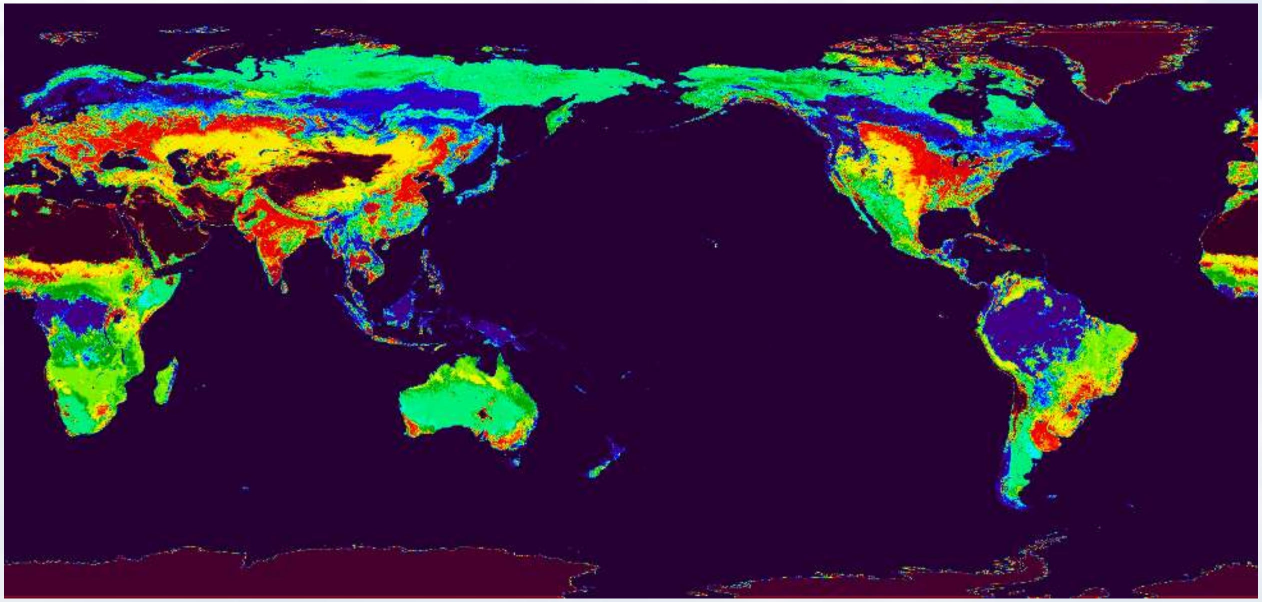
SAM Configuration for DYAMOND

- Grid 4608 x 9216 x 74 (0.039º x 0.039º, grid spacing 4.25 km at equator)
- Block topography at 4 km resolution; no smoothing except for Antarctica
- Single-Moment microphysics; CAM3 radiation called every 15 min
- Land: Simplified Land Model (Lee and Khairoutdinov 2015), 16 IGBP types, interactive snow
- Soil: 9 layers with thicknesses from 1 cm to 1 m; total depth 2.5 m
- Period: August 1st - September 10, 2016
- Performance: 6 simulated days per wall-clock day on 4608 cores (time step 7.5s)

Block-topography



16 IGBP land types

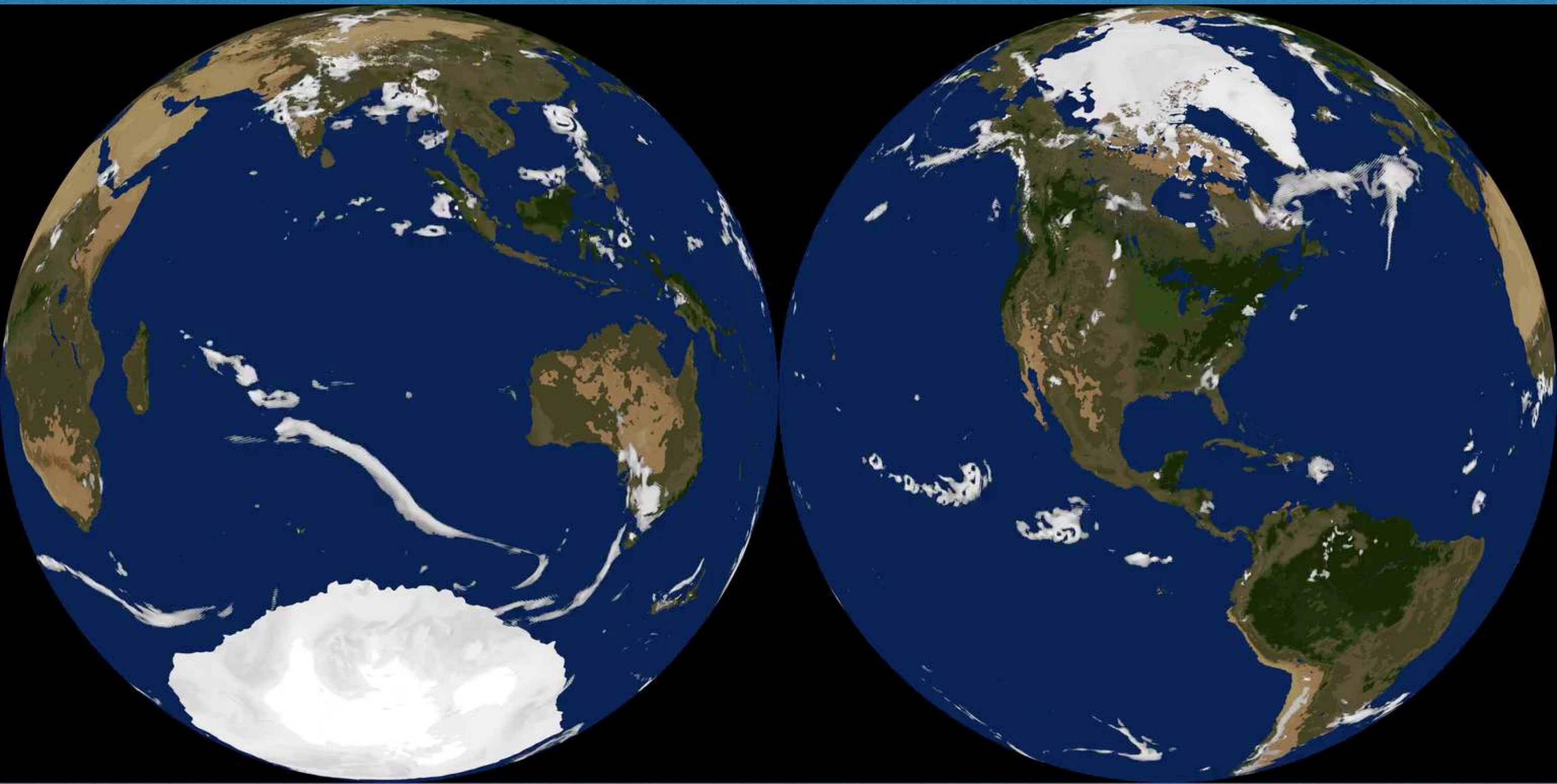


System for Atmospheric Modeling (SAM)

Grid spacing 4 km (0.039x0.039 deg)

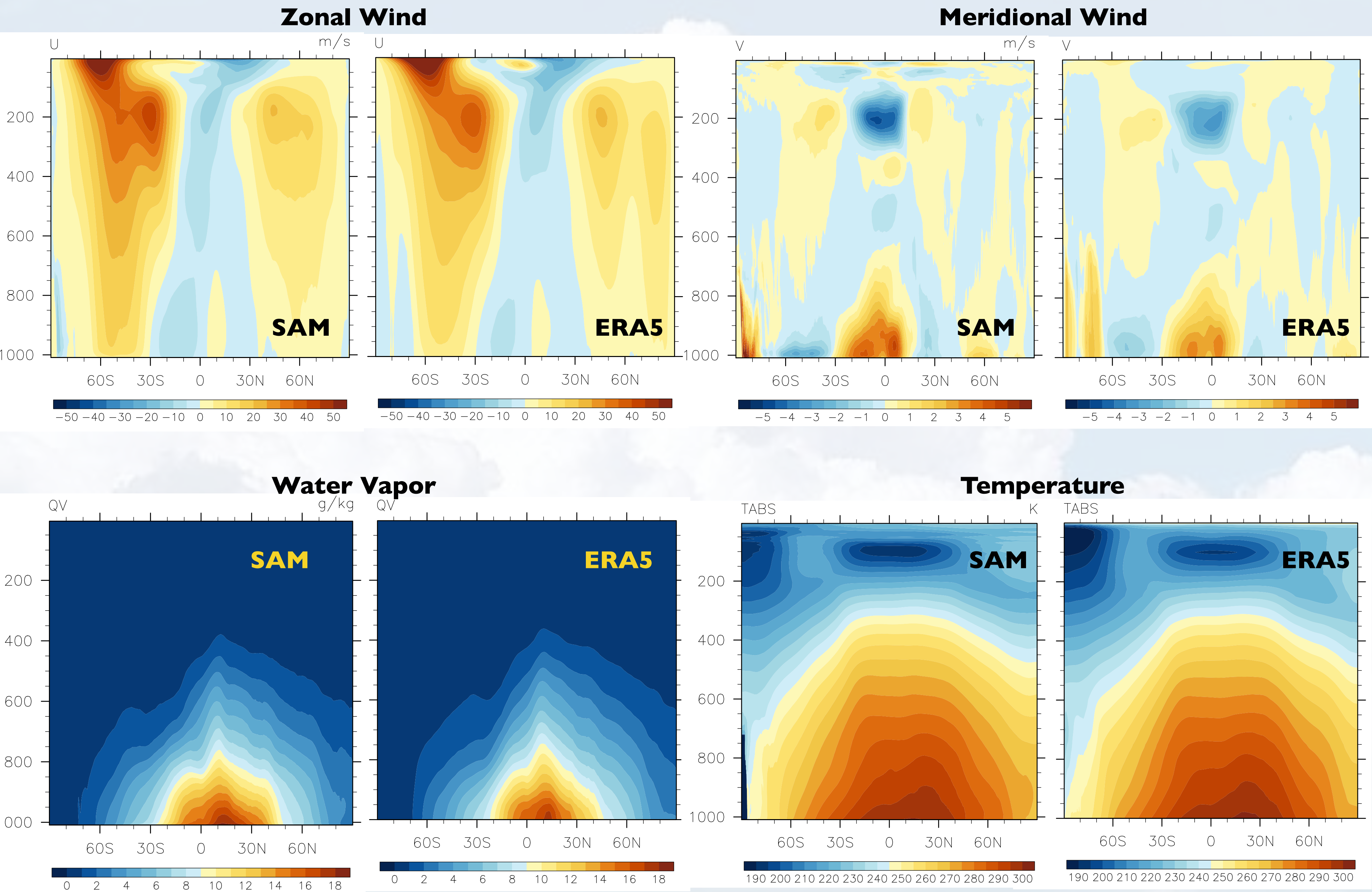
Aug 1 - Sep 10 2016

Cloud Albedo

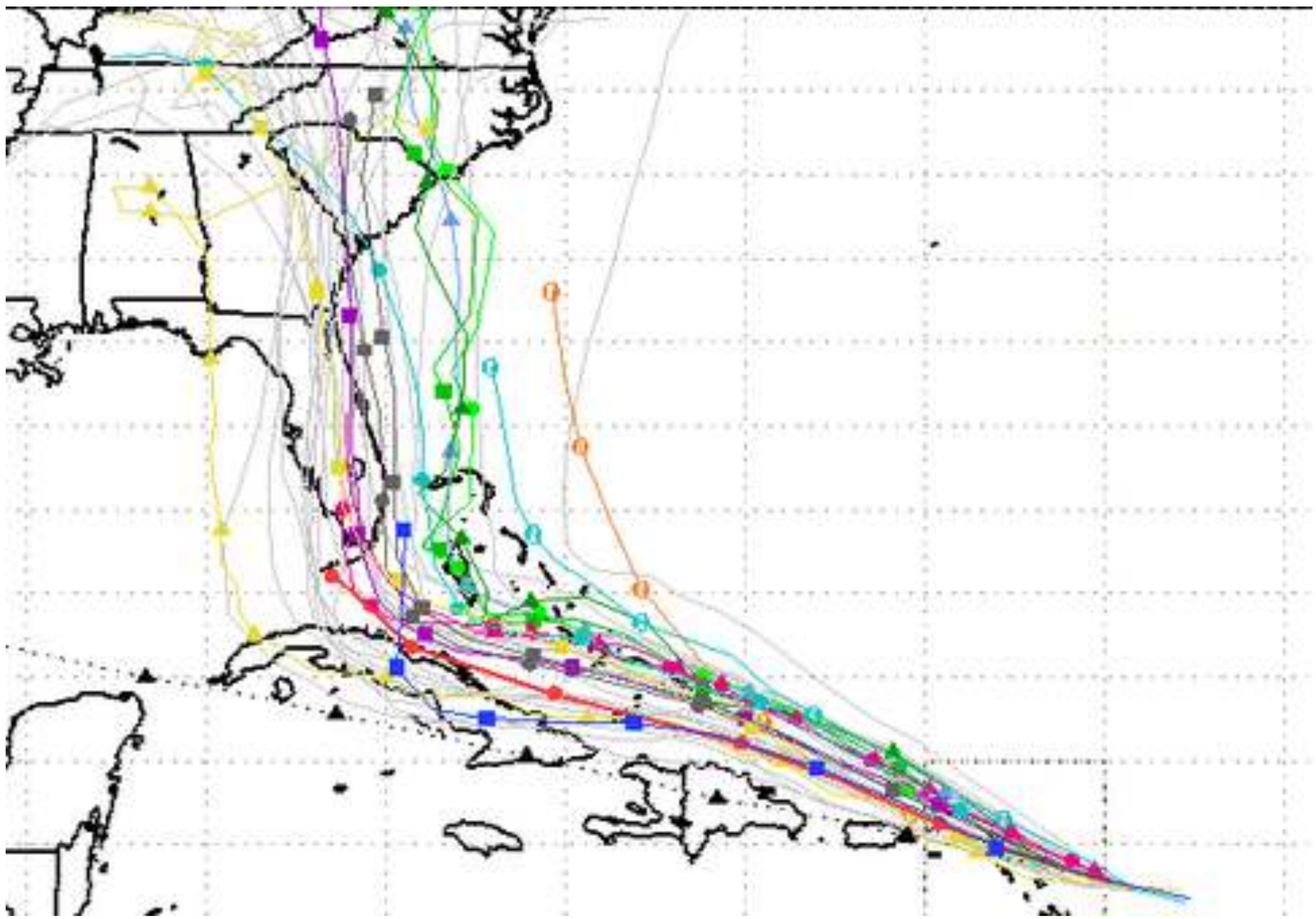


Performance: 6 times faster than real time on 4608 cores

Zonal-mean fields averaged over days 10-40



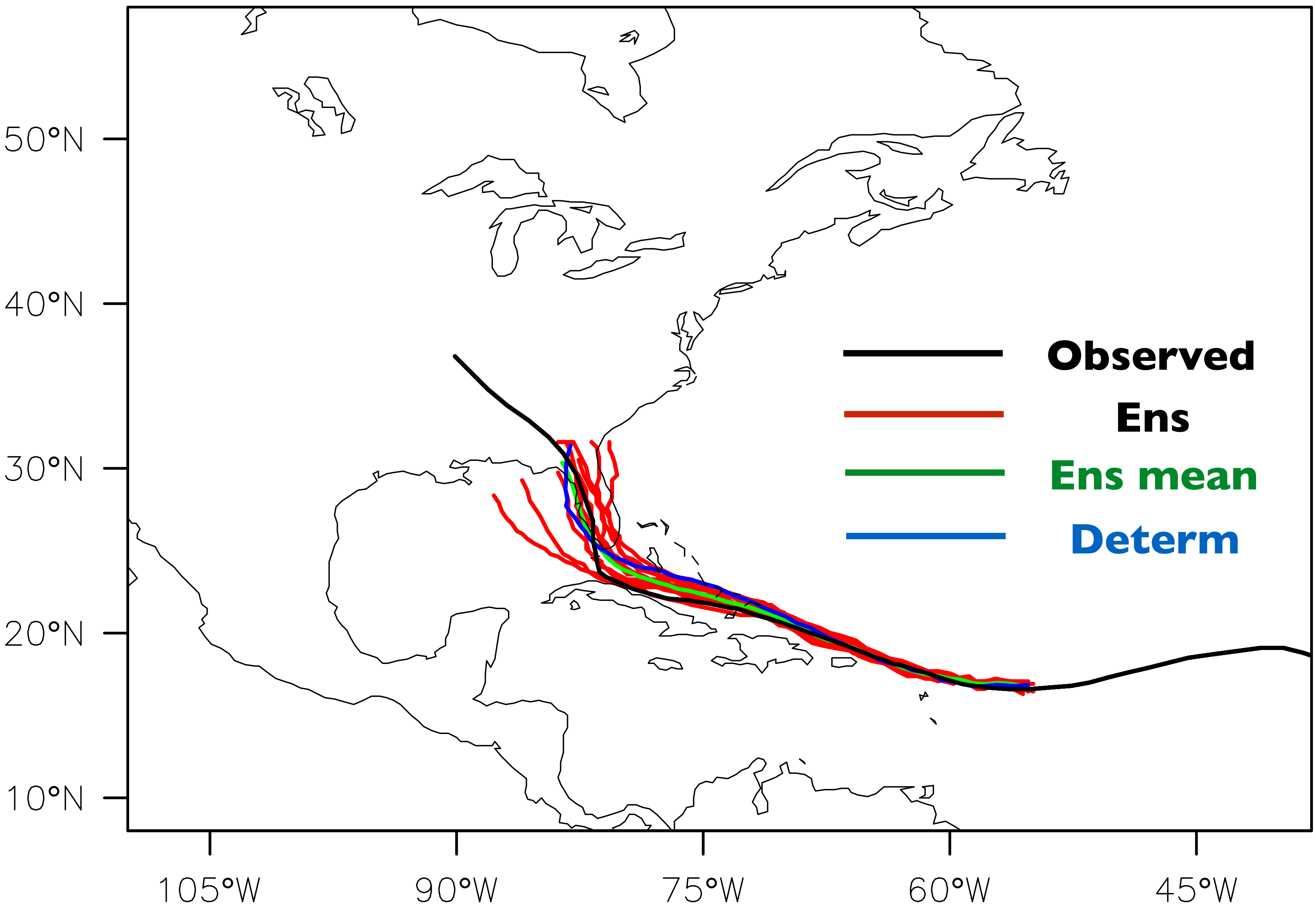
Hurricane Irma (2017)



'Spaghetti' plot for forecast of Irma on Sep 5, 2017

SAM's 7-day forecast of hurricane Irma (2017)

Initialization: 10-member ensemble from ERA5 on Sep 5, 2017
Ensemble resolution: 17 km (50 times faster real time)
Deterministic forecast: 4 km (6 times faster real time)



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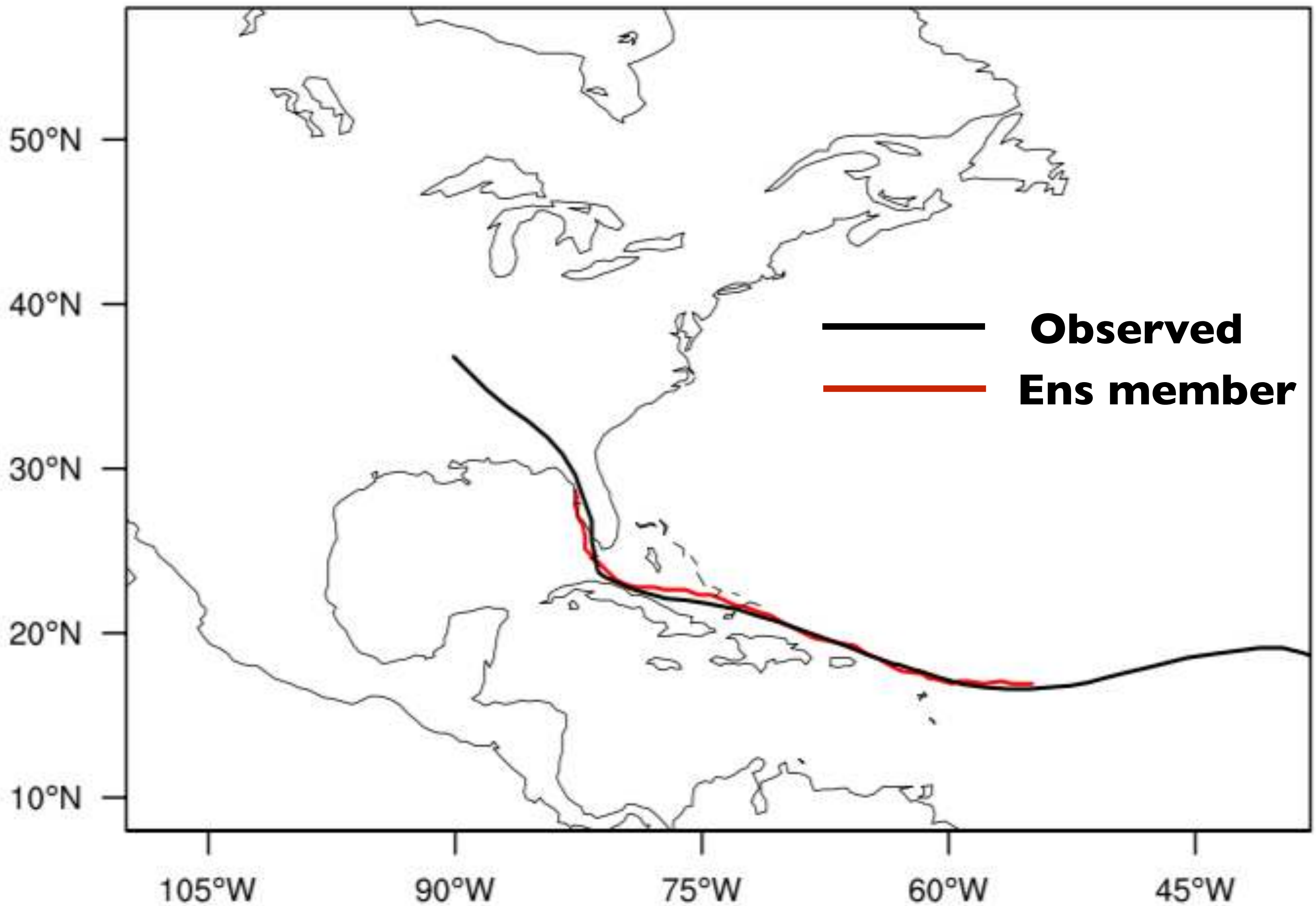
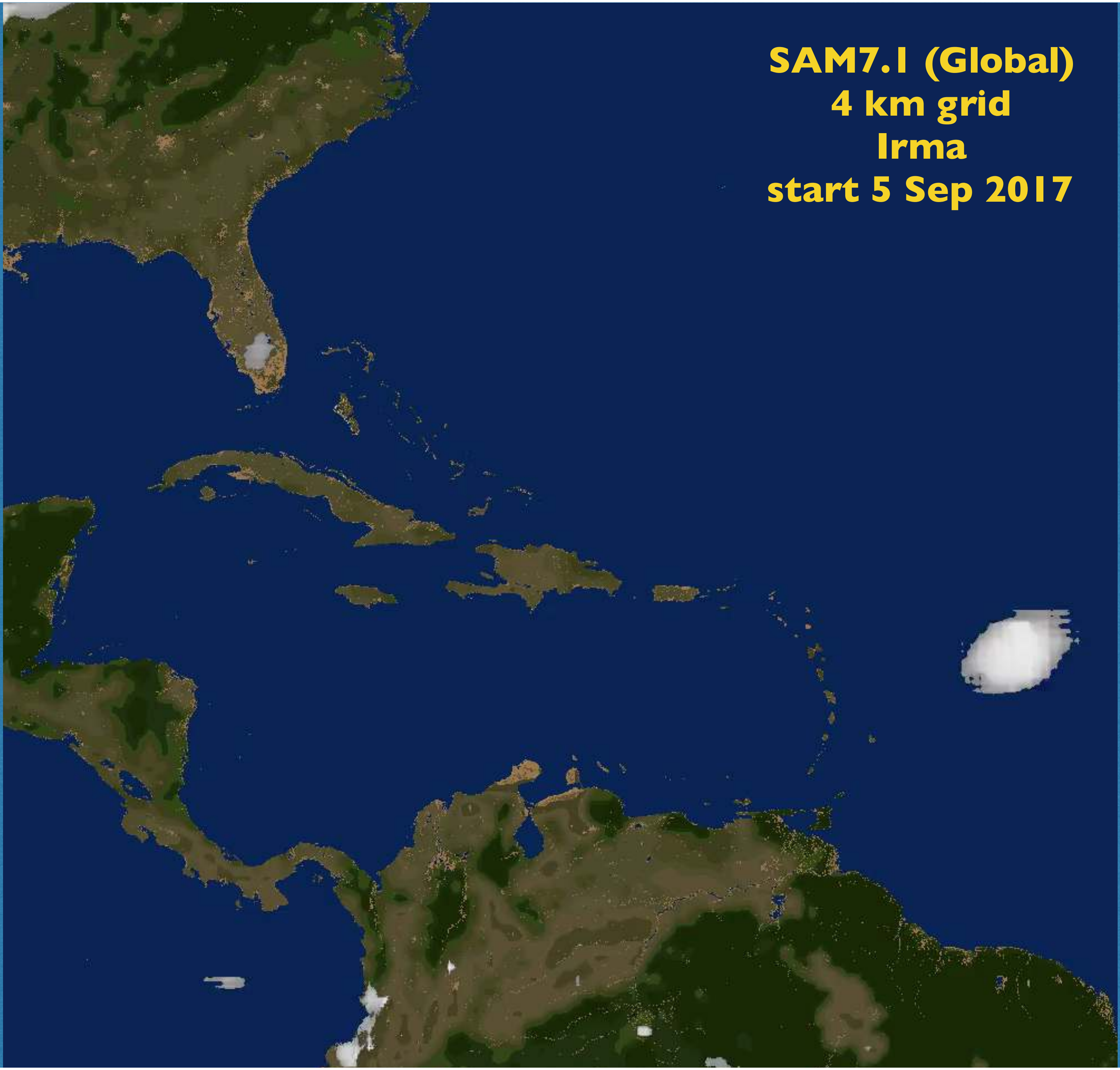
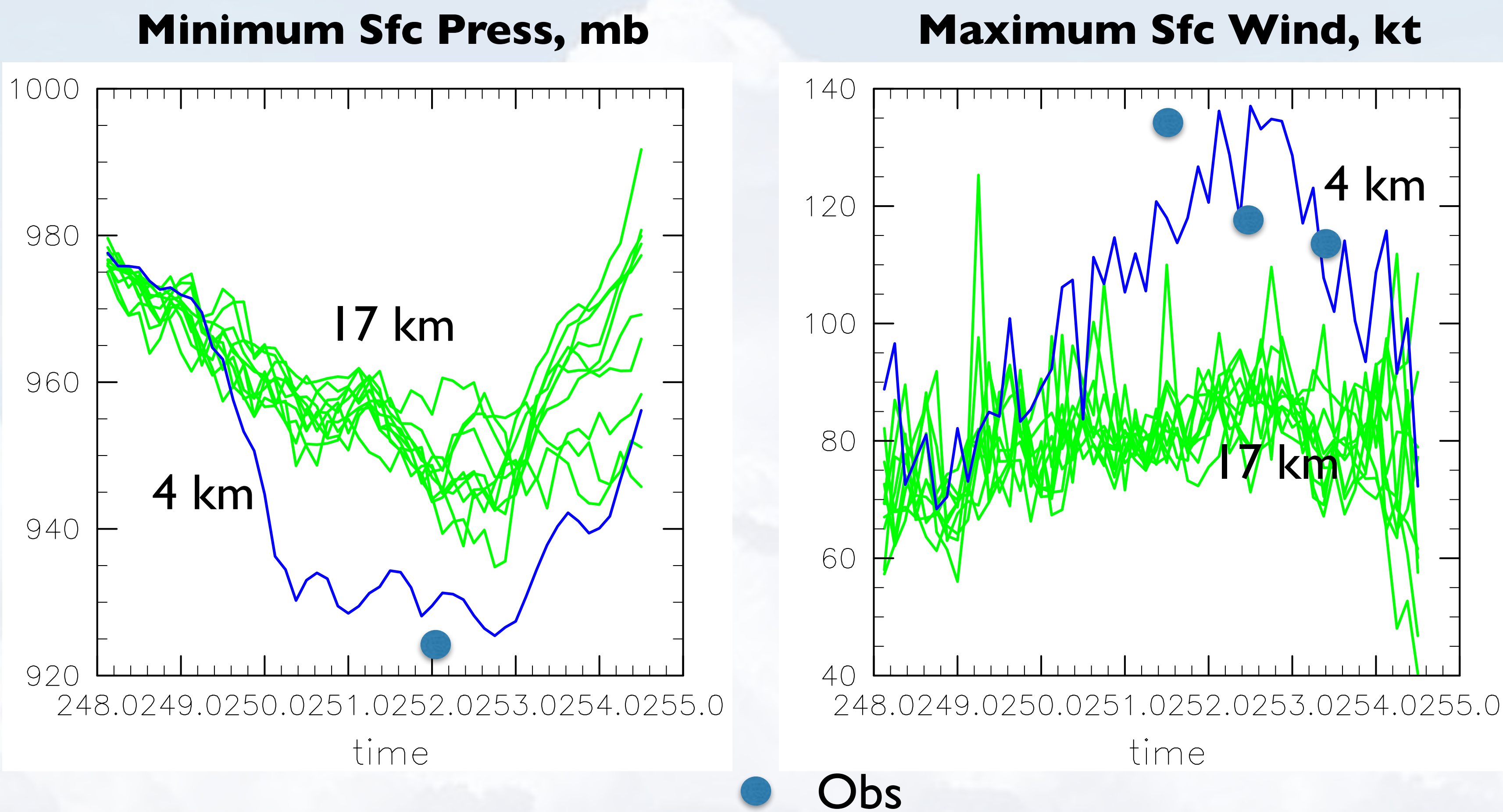



SAM7.1 (Global)
4 km grid
Irma
start 5 Sep 2017

7-day forecast of hurricane Irma (2017)

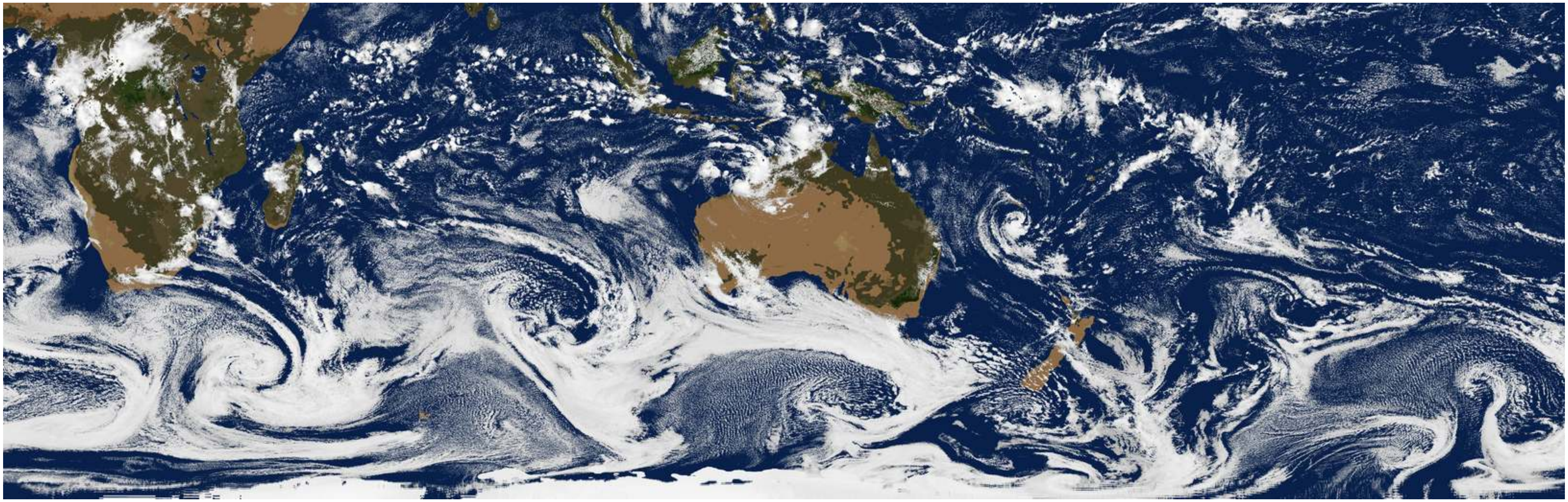


17-km grid simulation underestimate hurricane intensity.

4-km grid intensity and surface pressure agree well with observations.

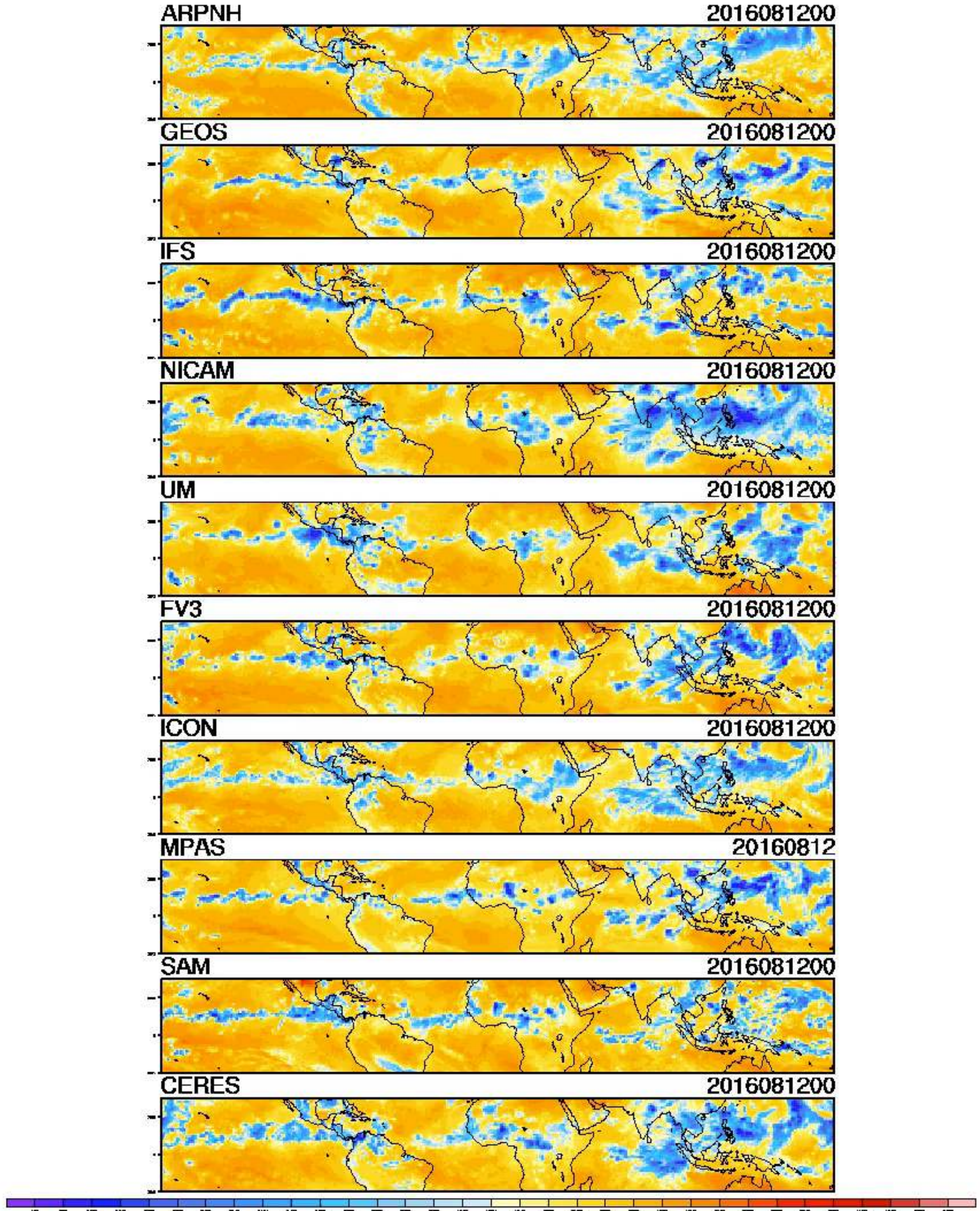
1-day forecast of SOCRATES

Feb 17 00Z



Preliminary results of Tropical-cluster Statistics in DYAMOND Models

1°x1° OLR



ARPNH 2016081200
GEOS 2016081200
IFS 2016081200
NICAM 2016081200
UM 2016081200
FV3 2016081200
ICON 2016081200
MPAS 20160812
SAM 2016081200
CERES 2016081200

Data

- DYAMOND models
  - OLR, ASR, Prec, PW on uniform 0.1° grid

- There is no equivalent high-resolution (space and time) observed global OLR
  - NOAA 11 μm 0.07° TBB, hourly
  - CERES 1° OLR hourly

- Which threshold for OLR to use for identifying deep convection?
  - 400 mb temperature in Tropics is 254 K
  - Inoue et al (2008), for NICAM used 210 W/m2 from cumulative histograms of OLR and TBB
  - This study: Use NOAA 0.07° TBB averaged to 1° and find CERES OLR threshold that produces similar PDF of cluster sizes

Data

- **DYAMOND models**
  - **OLR, ASR, Prec, PW on uniform 0.1° grid**

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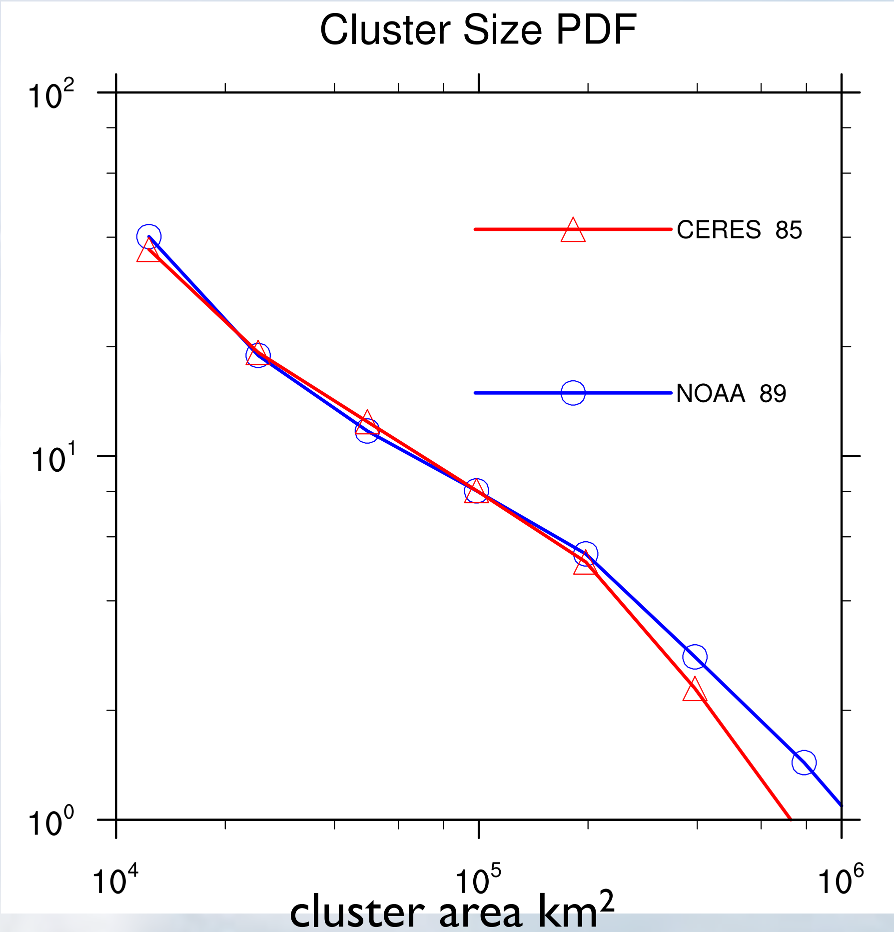
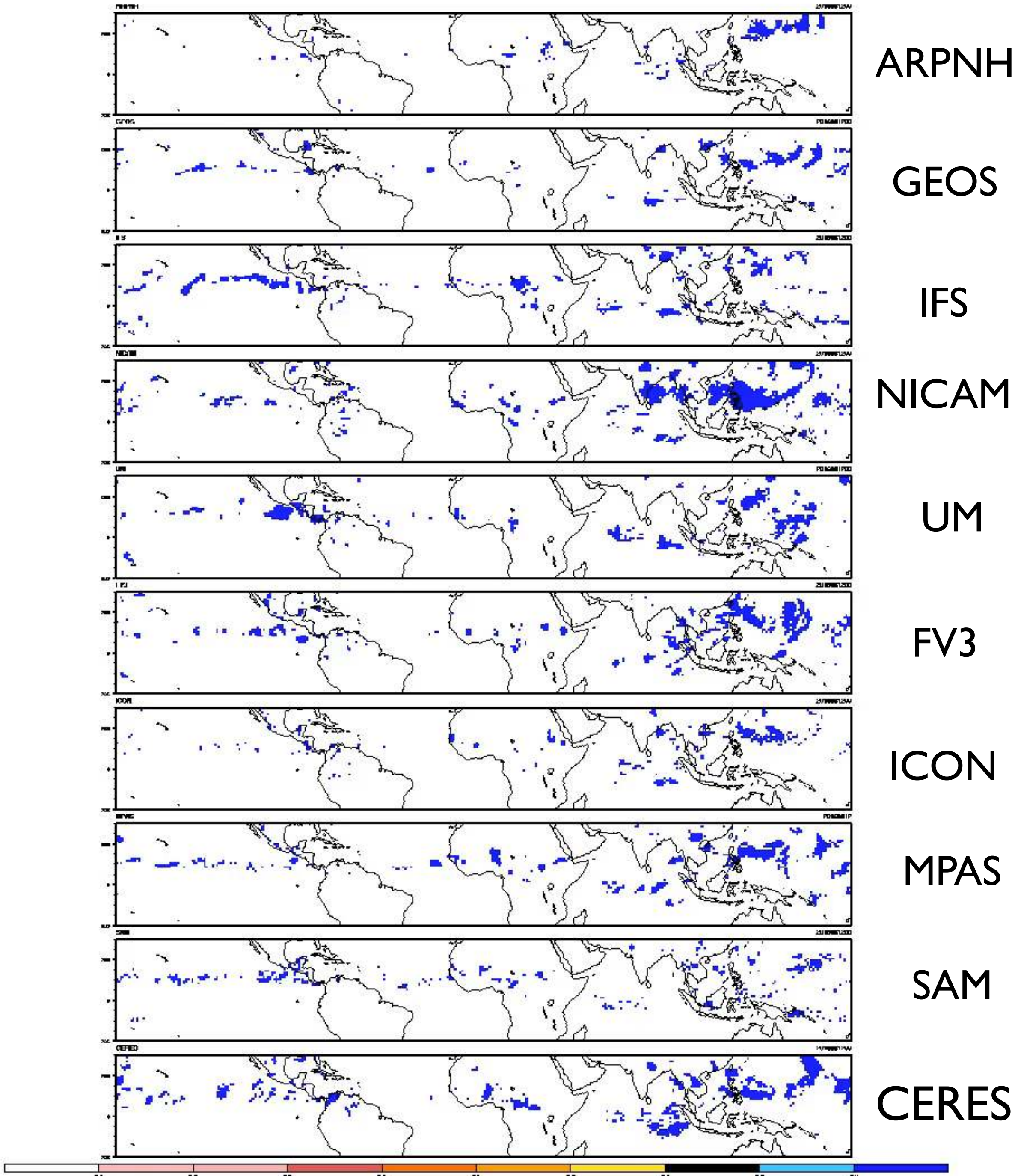
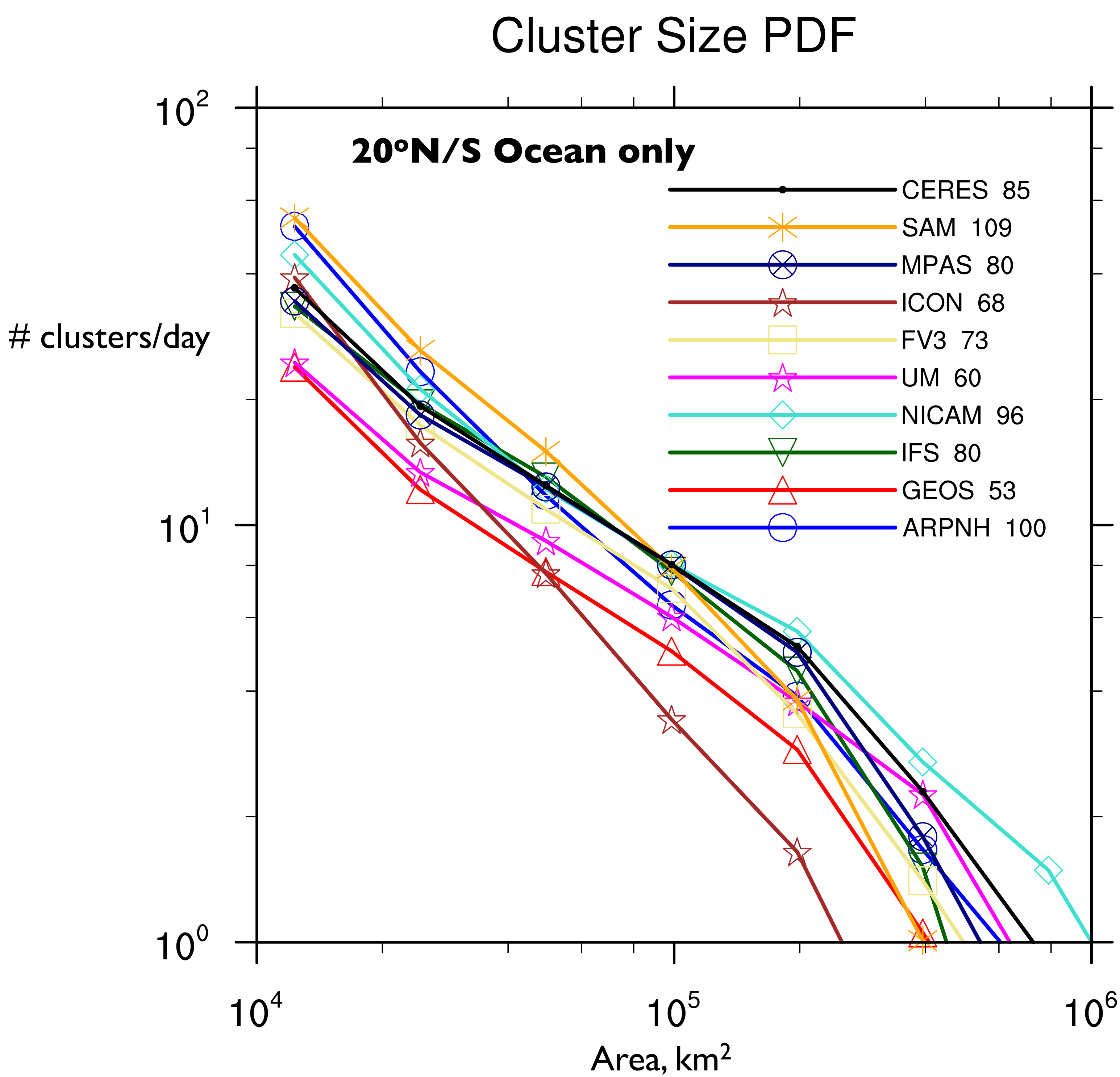
  - **This study: Use NOAA 0.07° TBB averaged to 1° and find CERES OLR threshold that produces similar PDF of cluster sizes**
  - **Best correspondence for OLR = 160 W/m2**



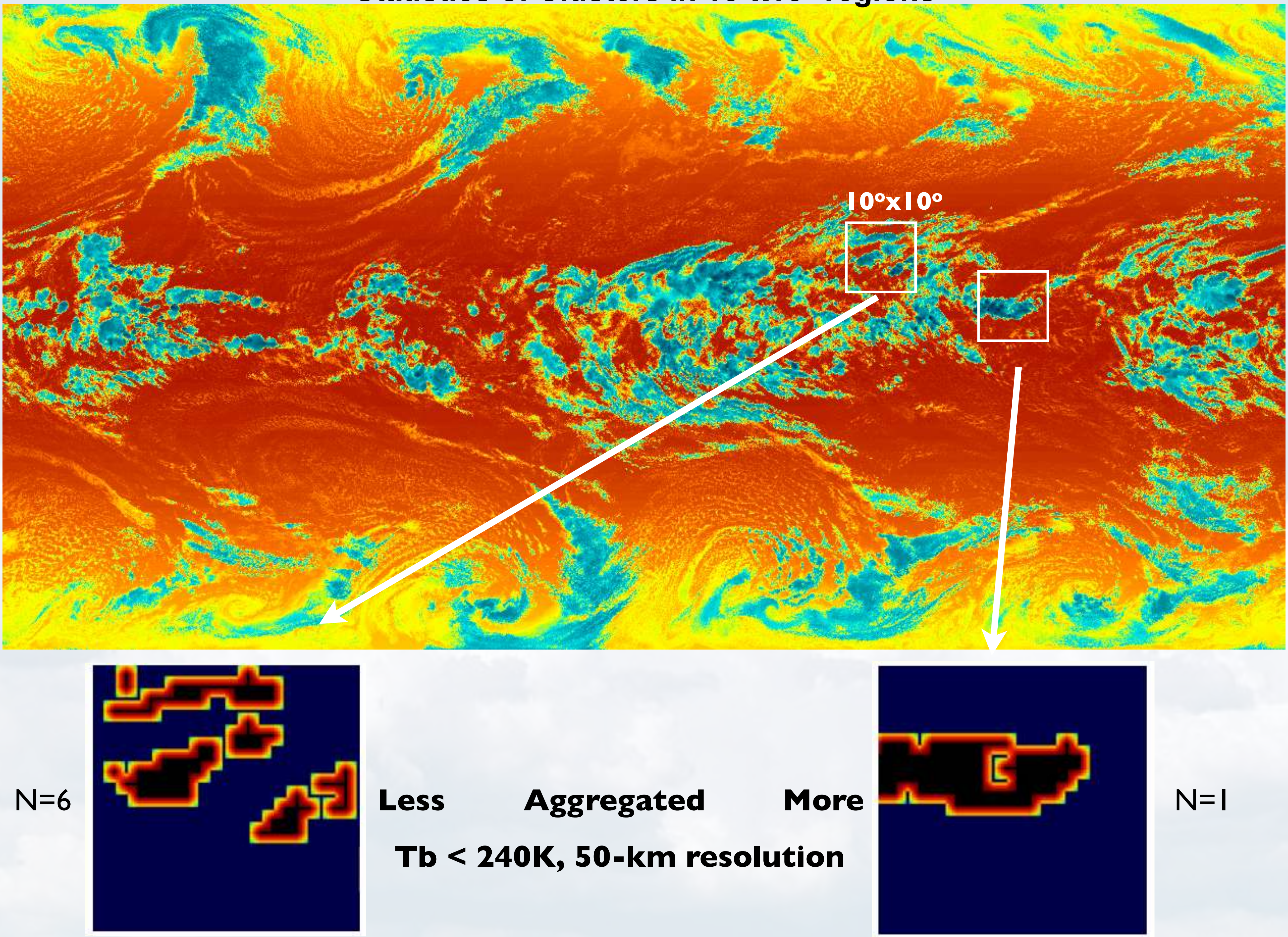
1° OLR < 160 W/m2

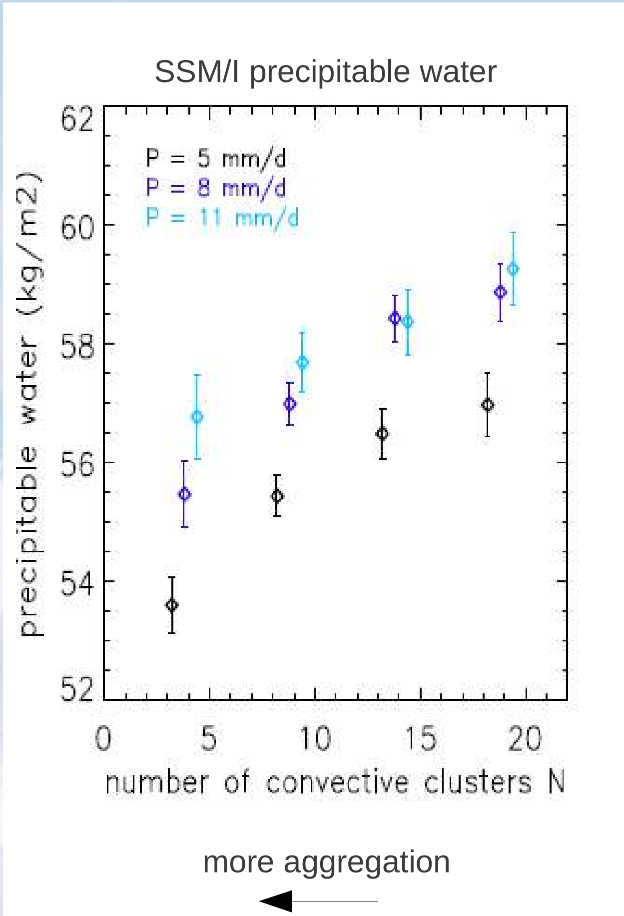


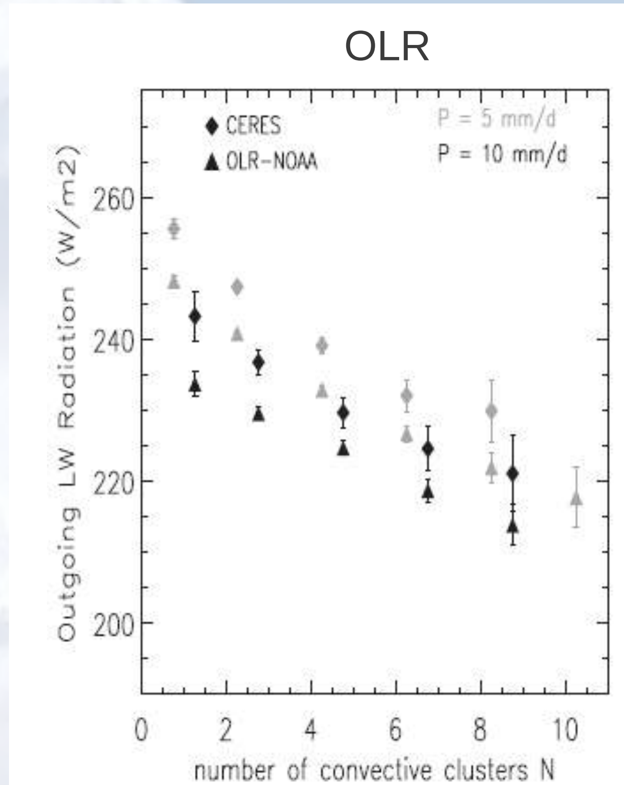


Cluster Size PDF
20°N/S Ocean only
CERES 85
SAM 109
MPAS 80
ICON 68
FV3 73
UM 60
NICAM 96
IFS 80
GEOS 53
ARPNH 100
clusters/day
Area, km²
10²
10¹
10⁰
10⁴
10⁵
10⁶

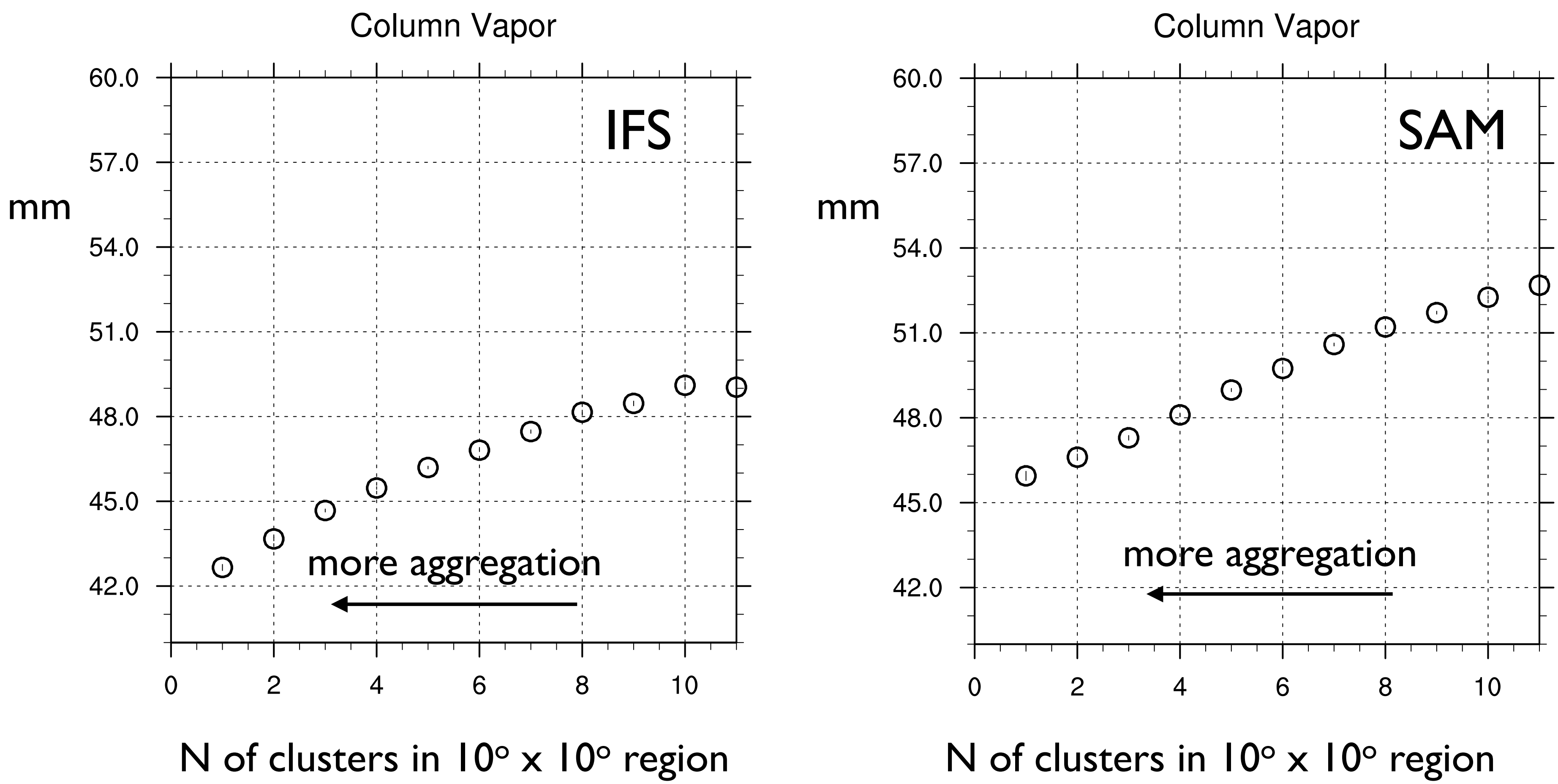
Statistics of Clusters in 10ºx10º regions

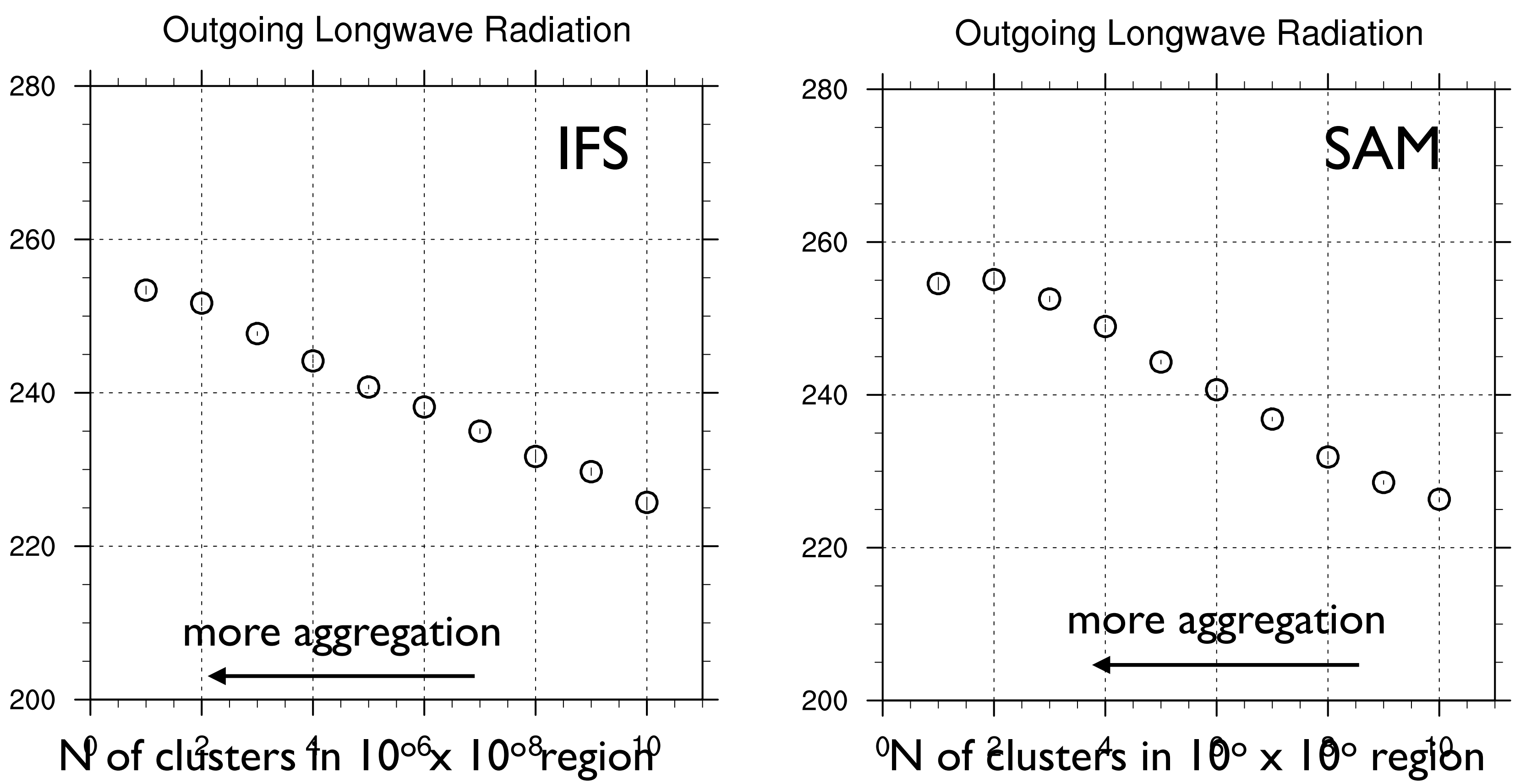






Tobin et al (2012, 2013):


Column Vapor
IFS
mm
60.0
57.0
54.0
51.0
48.0
45.0
42.0
more aggregation
0
2
4
6
8
10
N of clusters in 10° x 10° region
Column Vapor
SAM
mm
60.0
57.0
54.0
51.0
48.0
45.0
42.0
more aggregation
0
2
4
6
8
10
N of clusters in 10° x 10° region



Outgoing Longwave Radiation
IFS
more aggregation
280
260
240
220
200
0
2
4
6
8
10
N of clusters in 10° x 10° region
Outgoing Longwave Radiation
SAM
more aggregation
280
260
240
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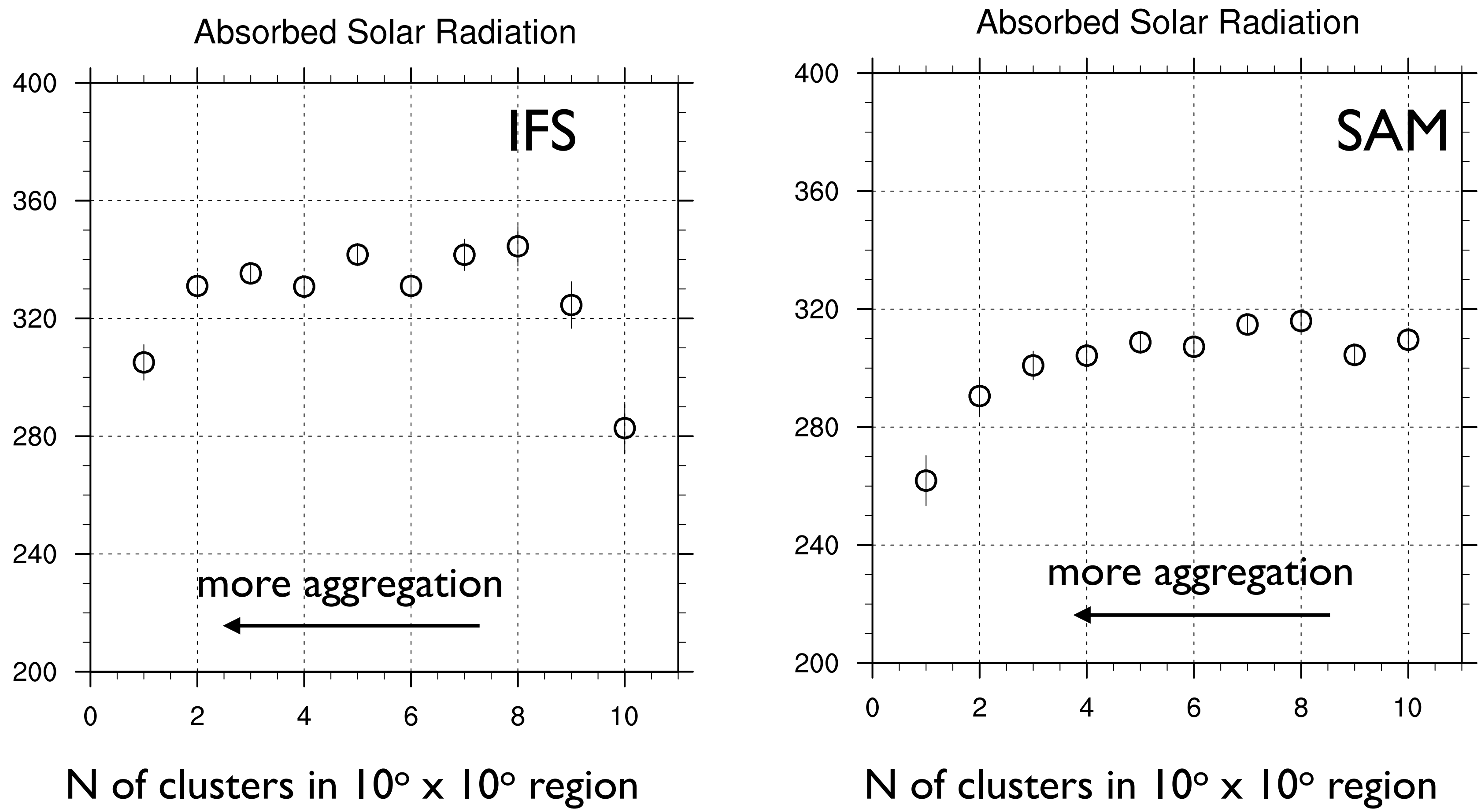
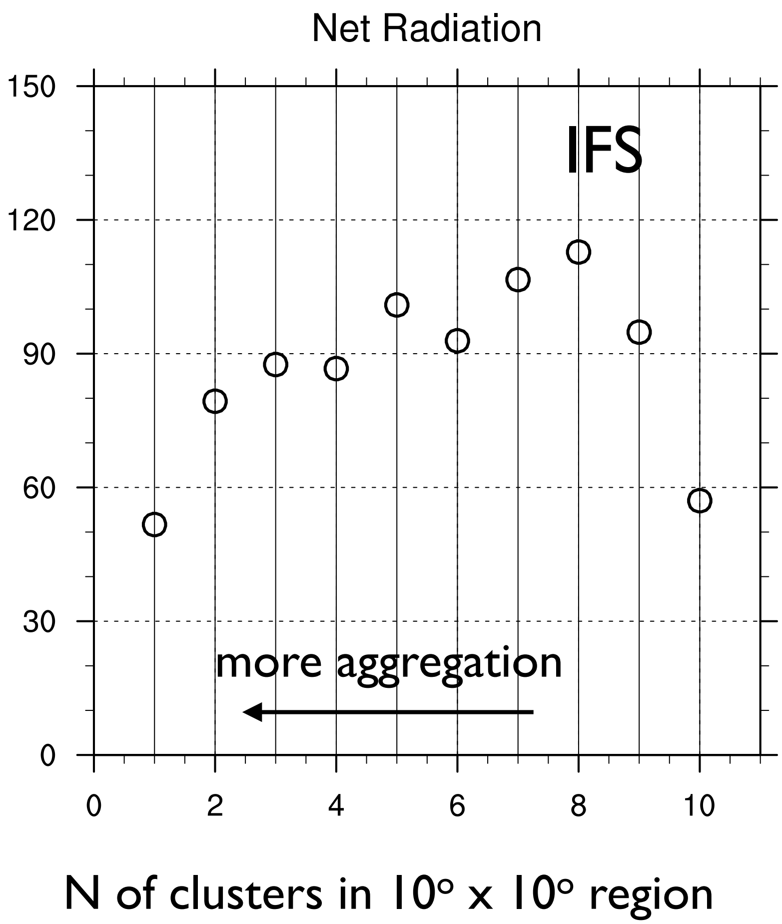
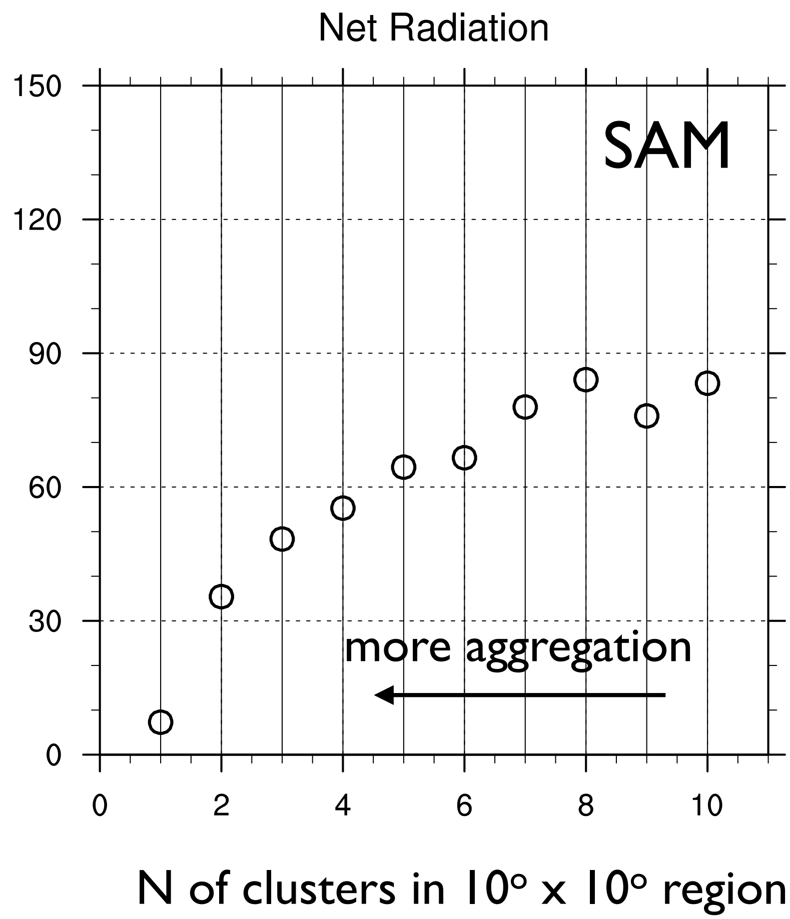

Absorbed Solar Radiation
IFS
more aggregation
N of clusters in 10° x 10° region
Absorbed Solar Radiation
SAM
more aggregation
N of clusters in 10° x 10° region

ASR - OLR at TOA





Organized convection seems to cool the climate system?