Climate and Earth System Science:

Use-inspired Research and Advancing the Frontiers

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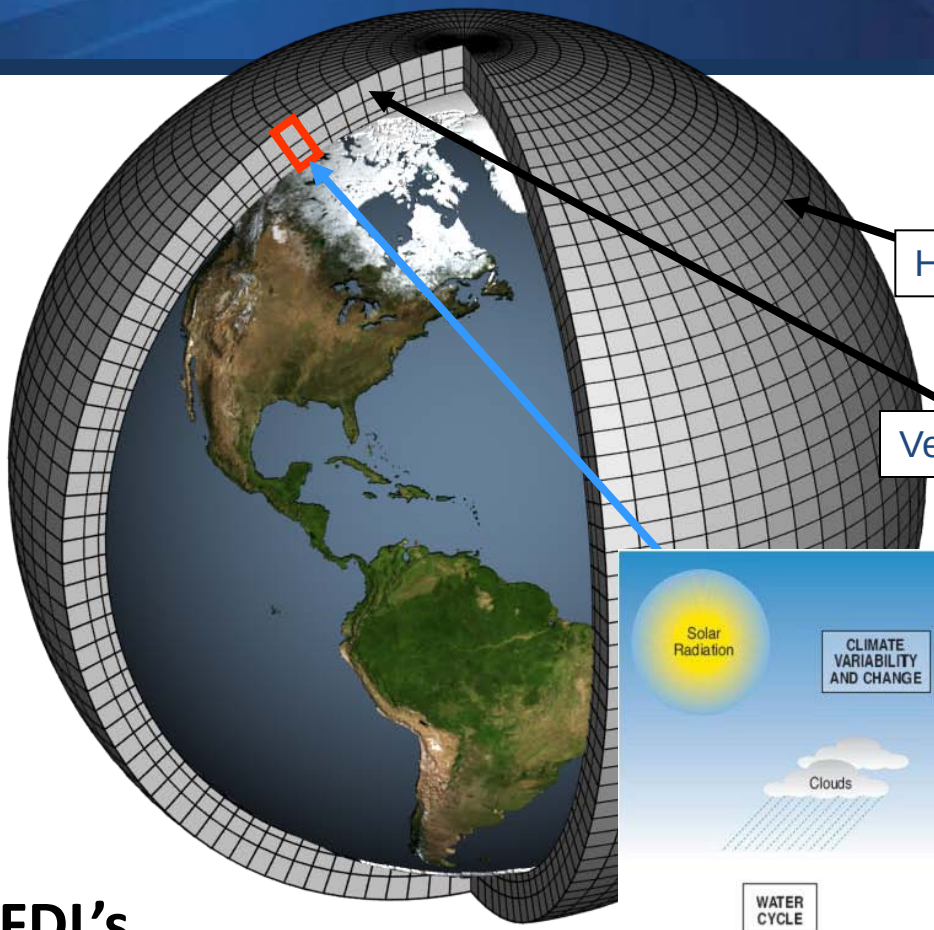
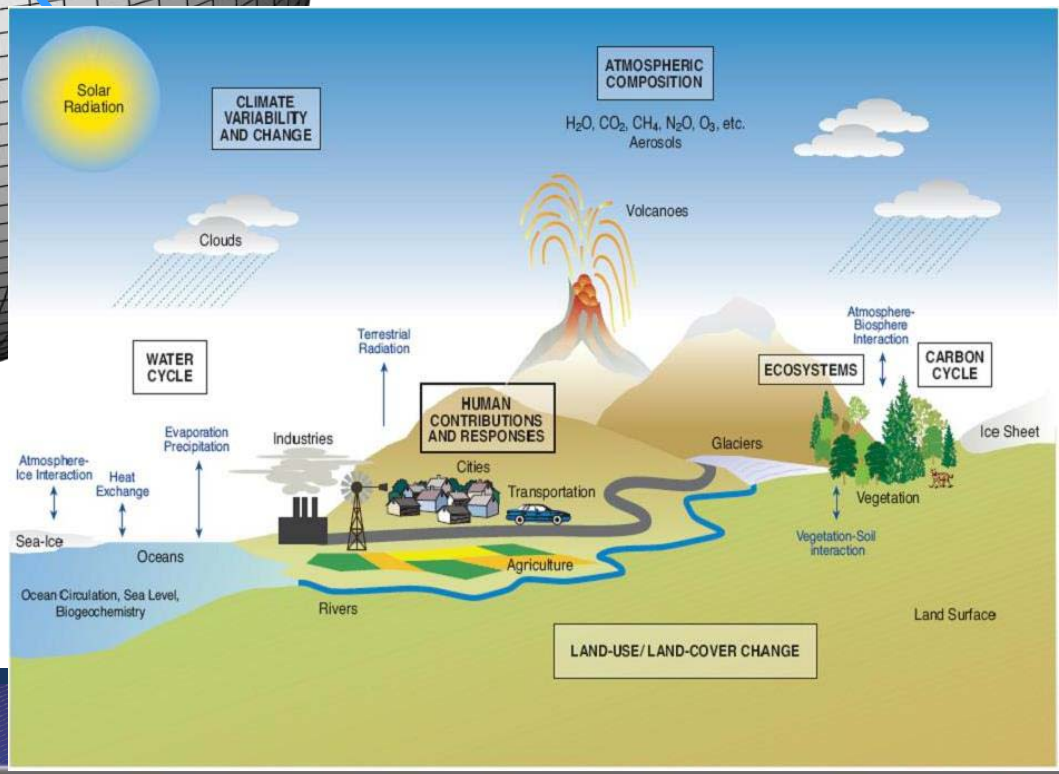
August 29, 2012

Schematic Global Climate Model



Horizontal Grid (Latitude-Longitude)

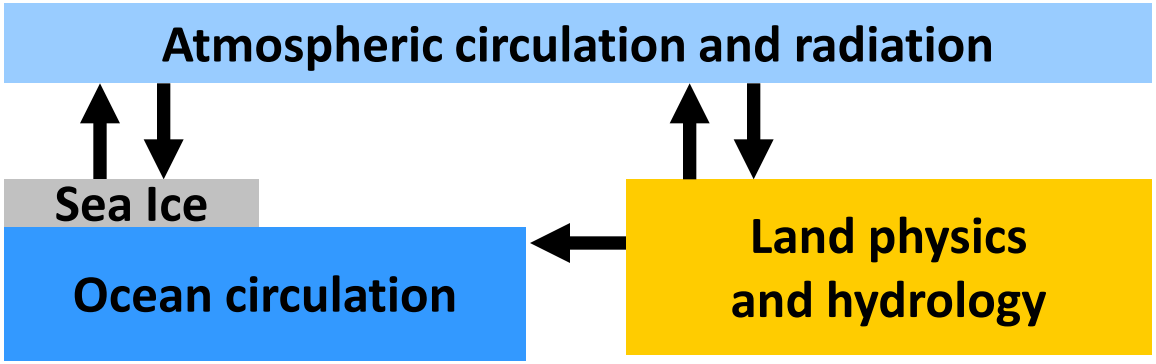
Vertical Grid (Height or Pressure)



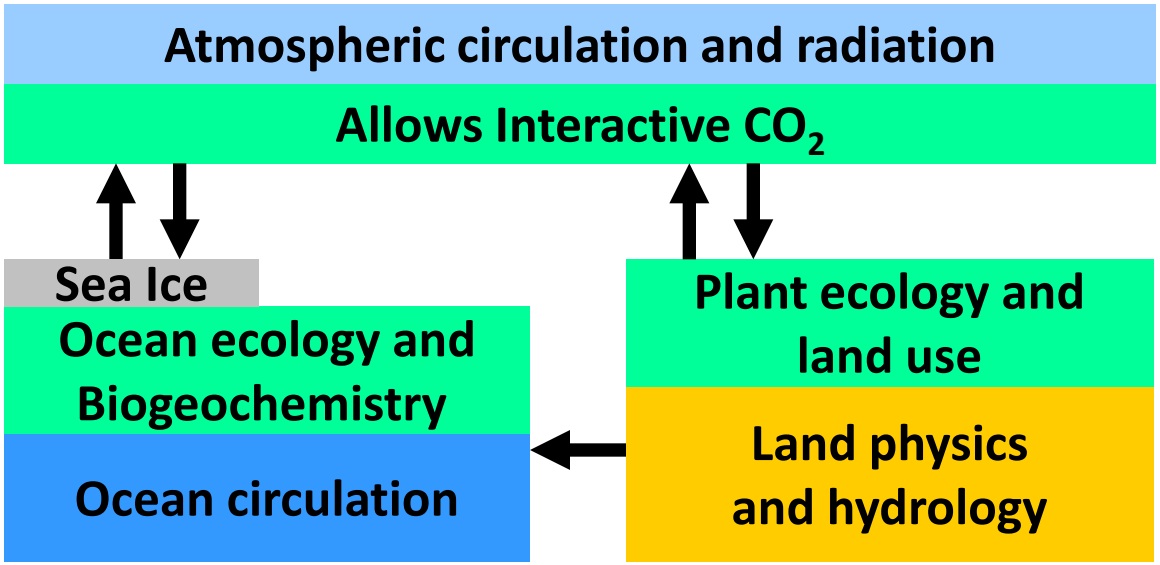
NOAA/GFDL's CLIMATE and EARTH SYSTEM MODELING

For CMIP5 and the IPCC
An Earth System Model (ESM) closes the carbon cycle

Climate Model

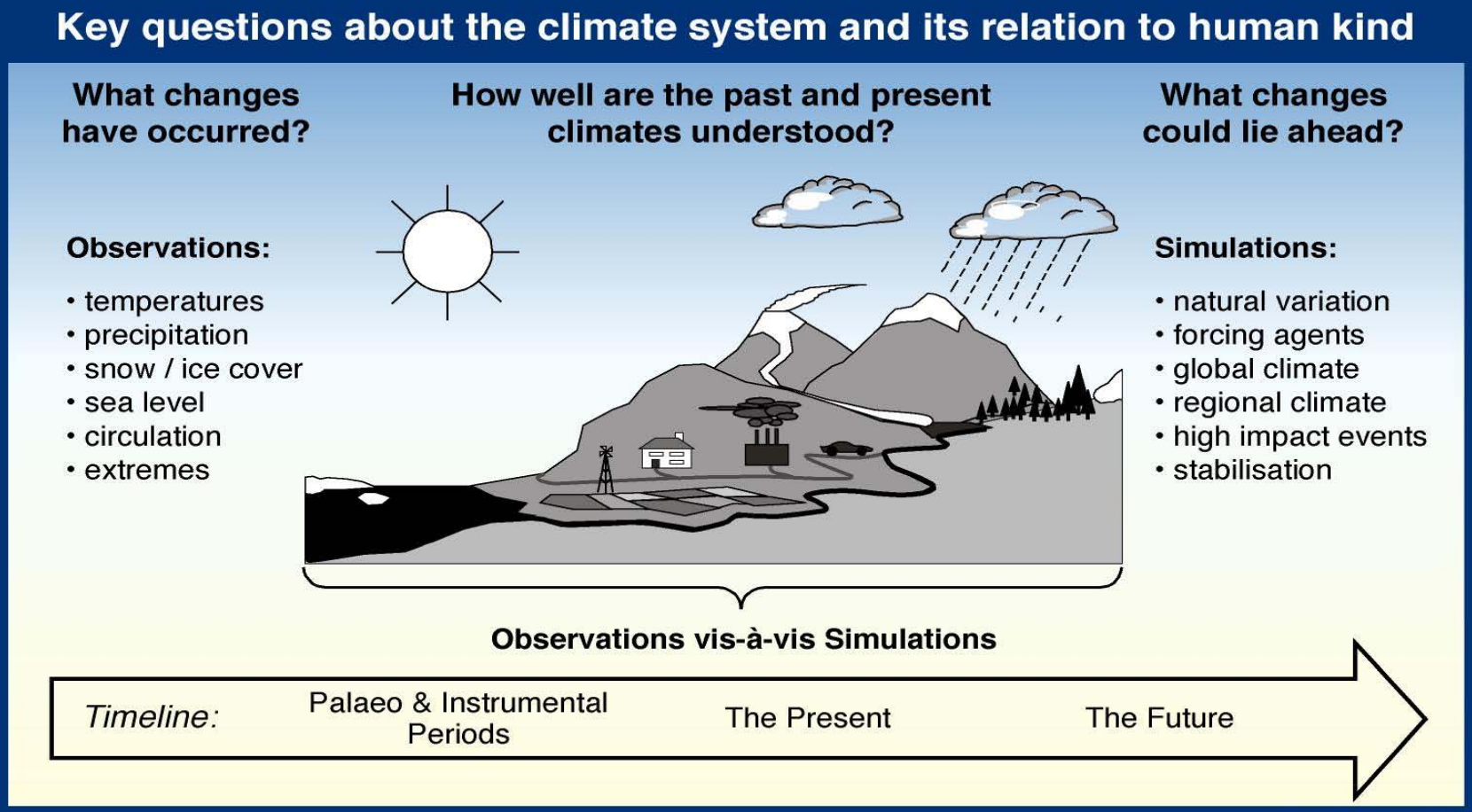


Earth System Model



*Many other definitions of an ESM

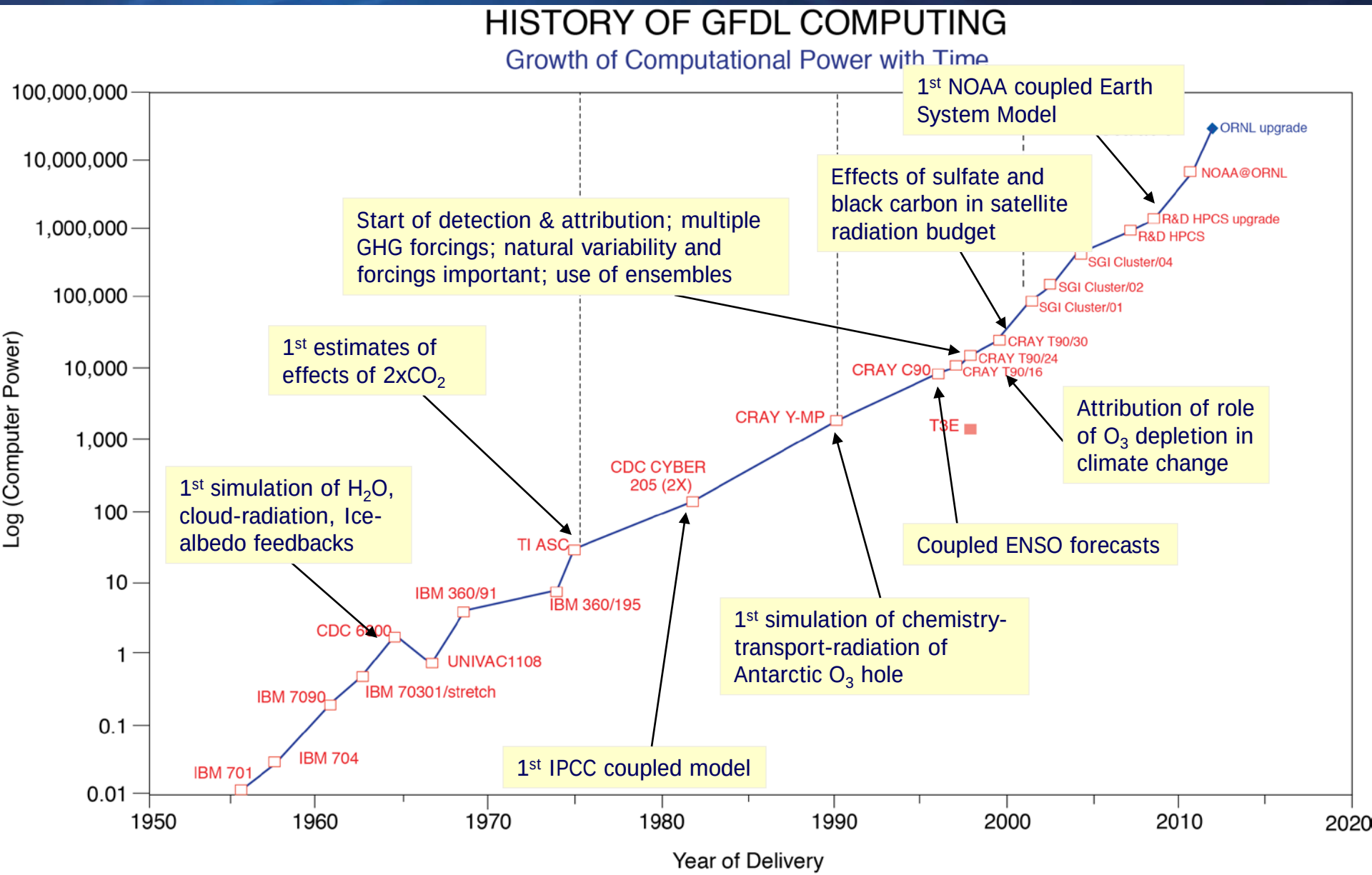
Why are models critically needed?



WG1 - TS FIGURE 1

Use-inspired scientific research:
The "Pasteur quadrant"

Scientific Advances are Linked to Computer Power



Planning, Execution, Results, Lessons

→ *advancing the frontiers of climate and ES science*

THEORY

NRC, other Reports

OBSERVATIONS

KNOWLEDGE & UNDERSTANDING

MODEL DEVELOPMENT

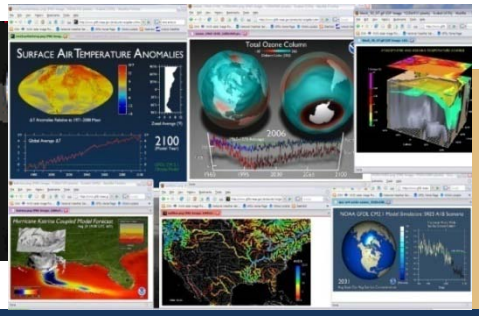
```
if (diagts .and. eots) then
  do 1500 m=1,nt
    do 1490 k=1,km
      fx = cst(j)*dyt(j)*dzt(k)/(c2dtts*dtxcel(k))
      do 1480 i=2,imtm1
        boxfx            = fx*dxt(i)*fm(i,k,jc)
        sddt             = (ta(i,k,m)-t(i,k,jc,nm,m))*boxfx
        svar             = (ta(i,k,m)**2-t(i,k,jc,nm,m)**2)
                           *boxfx
        n                = 0
        termbt(k,1,m,n) = termbt(k,1,m,n) + sddt
        tvar(k,m,n)      = tvar(k,m,n)      + svar
        n      = nhreg*(mskvr(k)-1) + mskhr(i,j)
        if (n .gt. 0 .and. mskhr(i,j) .gt. 0) then
          termbt(k,1,m,n) = termbt(k,1,m,n) + sddt
          tvar(k,m,n)      = tvar(k,m,n)      + svar
```

WELL-DESIGNED MODEL EXPERIMENTS

ANALYSIS OF MODEL RESULTS

OBSERVATIONS

Assessments



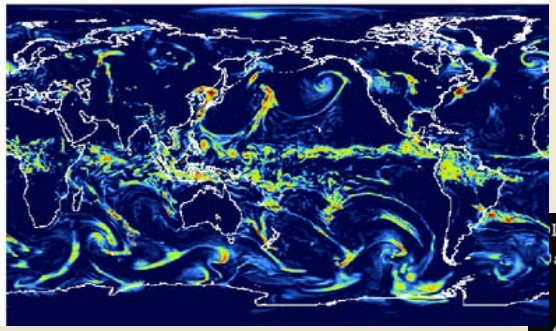
CMIP5/ IPCC AR5 Accomplishments

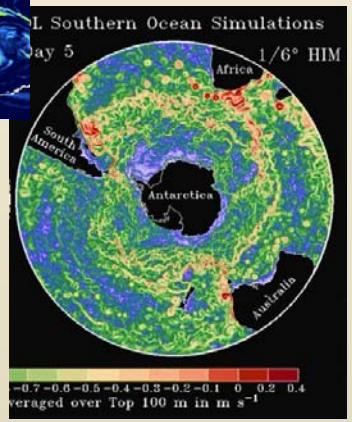
Stream	Total Model Years	CMIP5 Data (TB)
Physical Climate	6800	15.3
Earth System	18,500	119.2
High-resolution	500	22.3
Decadal Prediction	5000	7.3
TOTAL	**30,800**	**164.1**

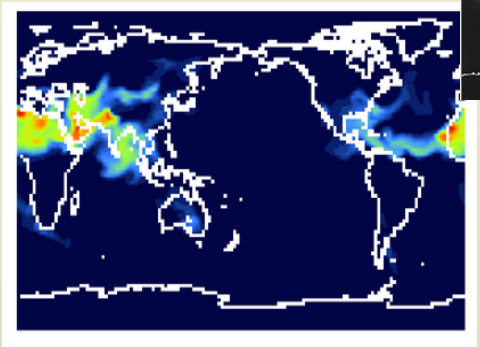
More than the entire world's model data archive for CMIP3/ IPCC AR4 (2007)

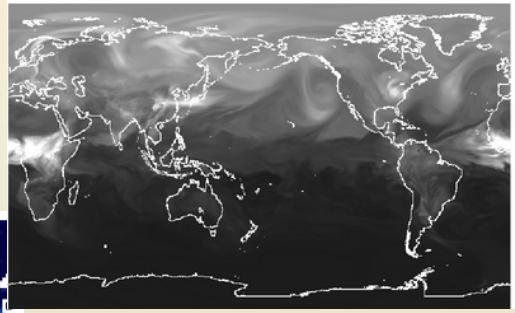
	Publications
FY11	**~70**
FY12	**39 to date (+55 submitted)**

NOAA/ GFDL Climate Modeling → Advancing the Science → Meeting the NGSP Climate Objectives



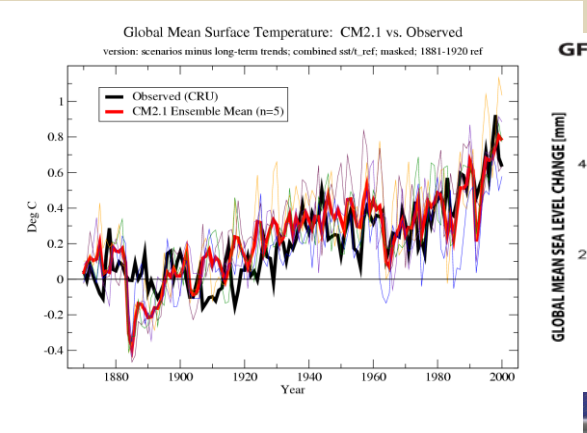


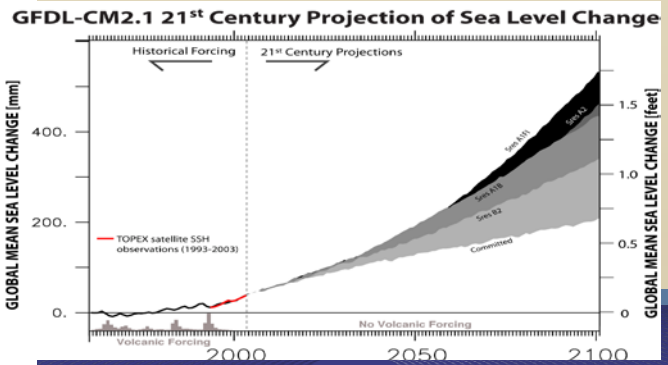




Resolution

Earth System Complexity





Current NOAA/ GFDL Climate Modeling

Contributions to CMIP5 and IPCC AR5 [Report in 2013]

<u>Advancing the understanding</u> of the climate and Earth System - the <u>processes, mechanisms, and interactions</u>

➔ reliable global- to regional-scale projections and predictions:

1. **Role of pollutant particulates and other short-lived species compared to long-lived gases such as carbon dioxide.**
2. **Carbon and other biogeochemical cycles, uptake of carbon by land and oceans, and their roles in climate change.**
3. **High-resolution, atmosphere-ocean models for seasonal- to-centennial variability, predictability and regional change.**
4. **High-resolution models for understanding "weather extremes" in climate (e.g. hurricanes, heat waves and droughts).**

Climate Change

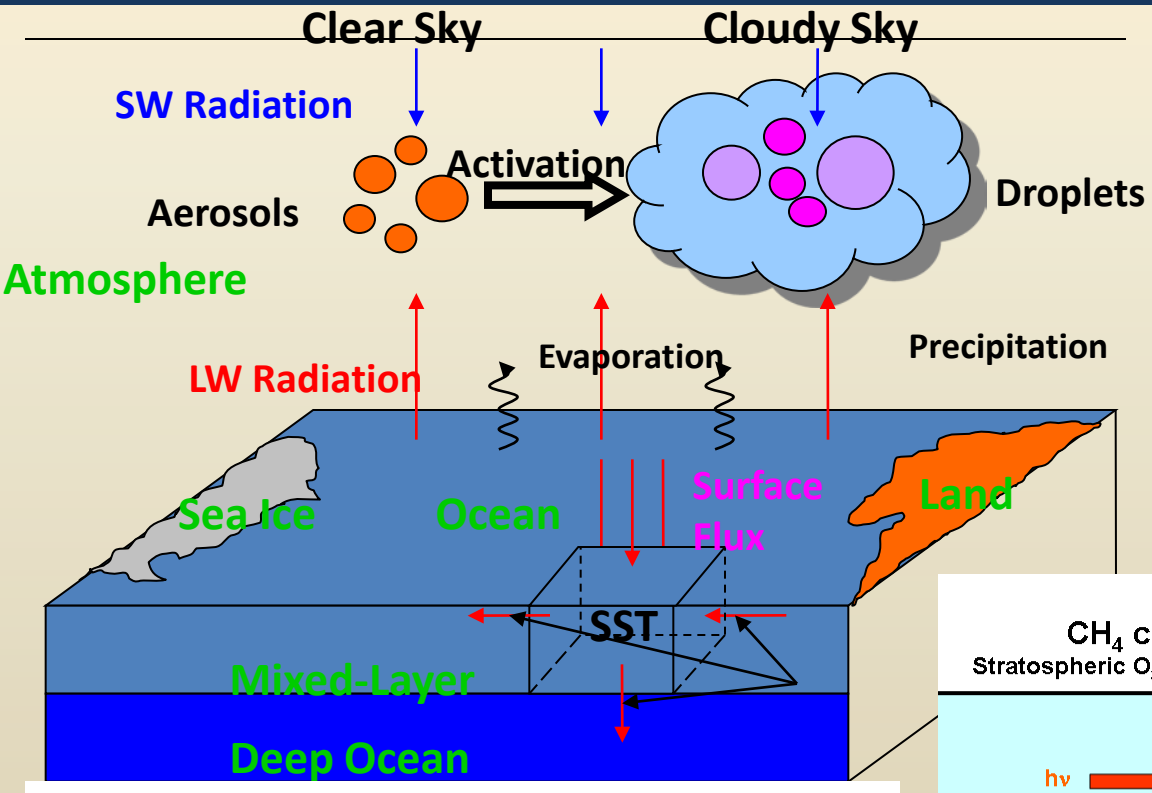
New NOAA/ GFDL Climate Model; AM3/ CM3

{Donner et al., 2011; Bollasina et al., 2011}

Greenhouse gases versus Aerosols

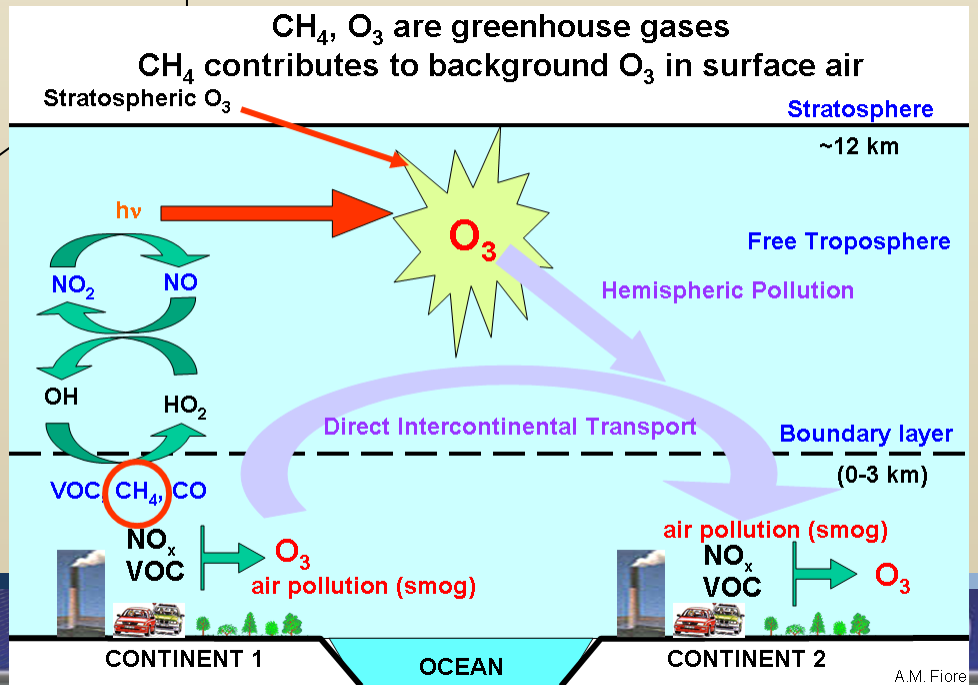
[Detection and Attribution of Climate Change]

Coupled Chemistry-Aerosol-Climate model



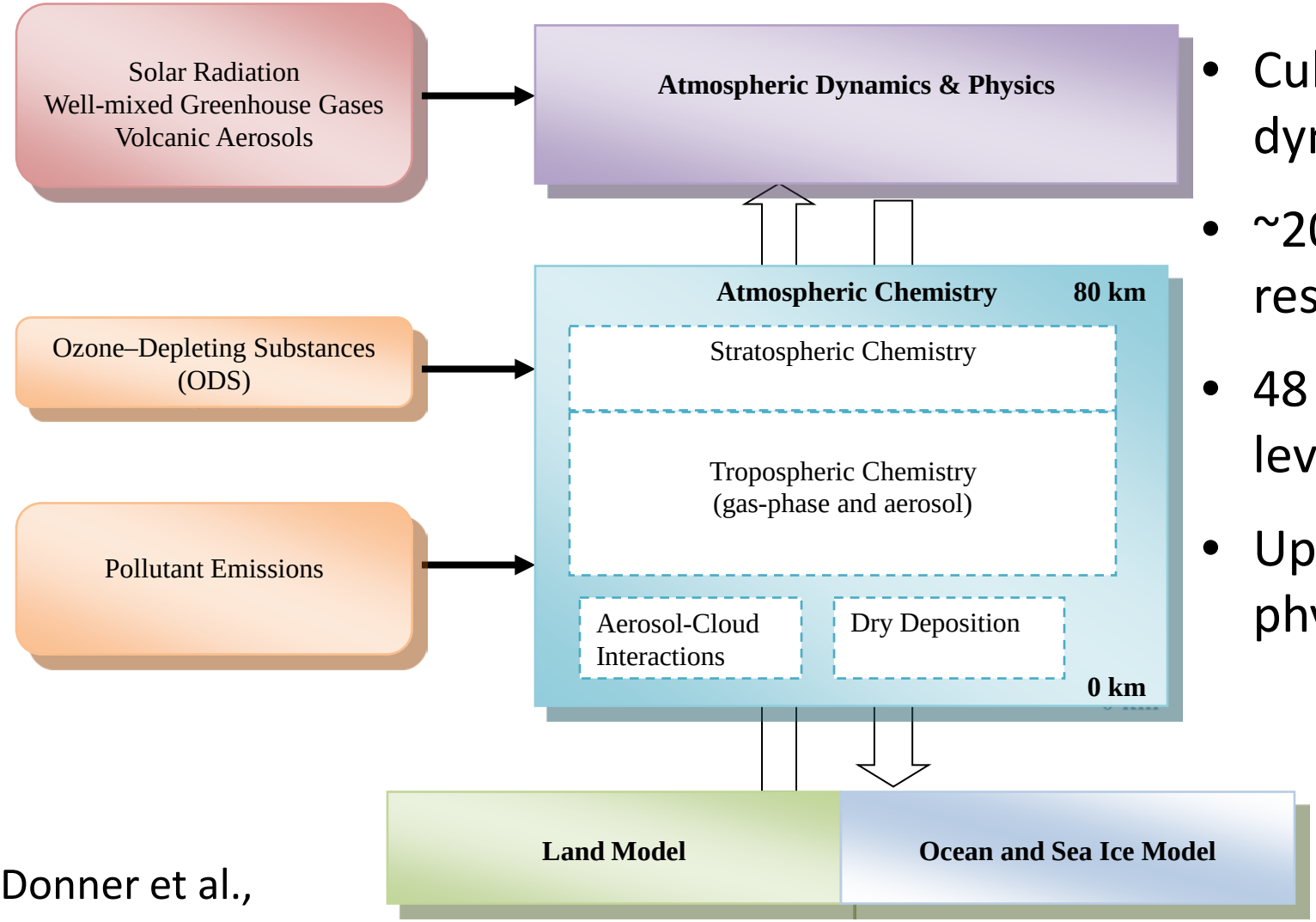
Aerosols and Climate

Global Air Quality and Climate



A.M. Fiore

CM3 Coupled Climate Model

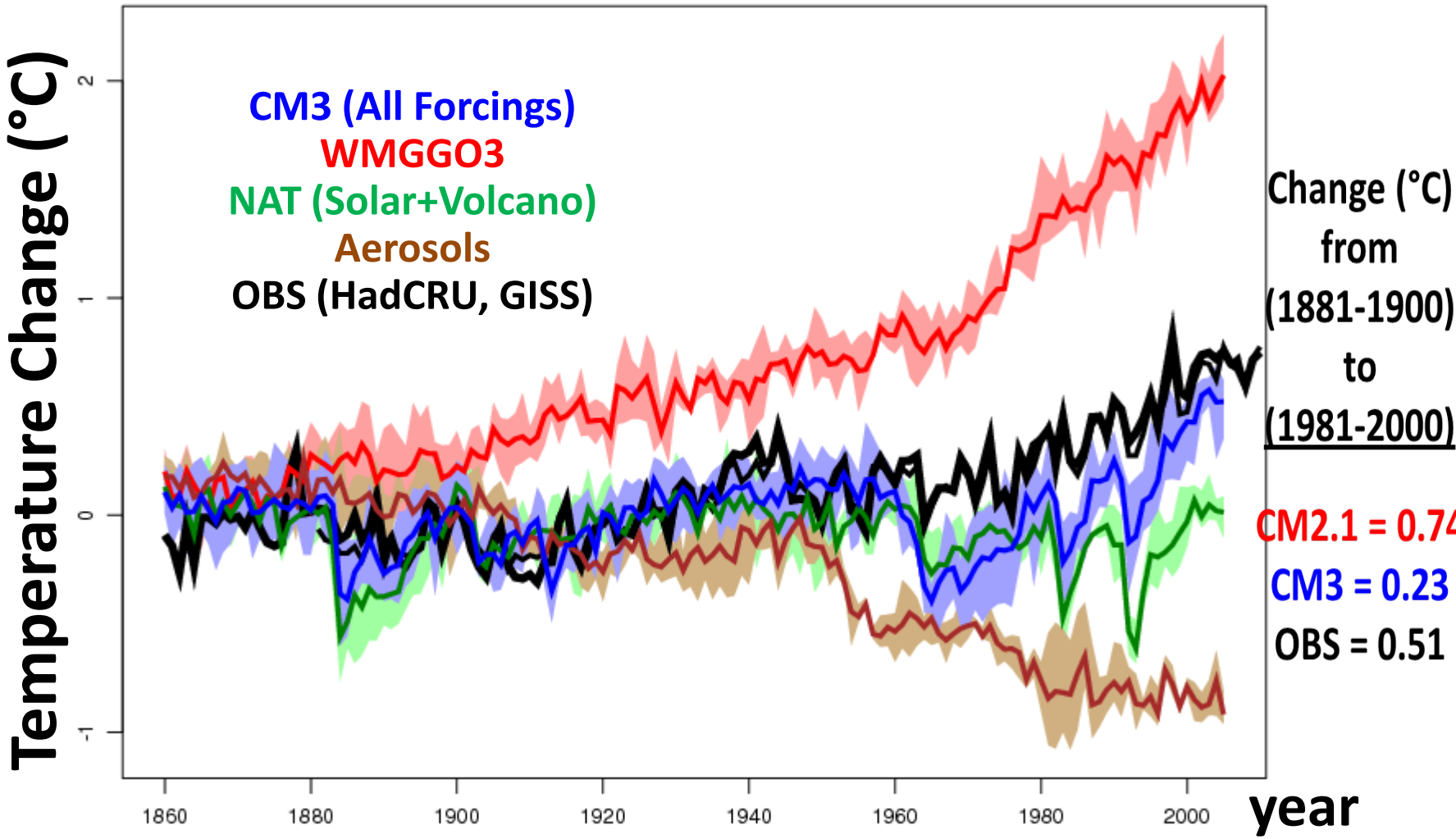


- Cubed-sphere dynamical core
- ~200km horiz. resolution
- 48 vertical levels
- Updated moist physics

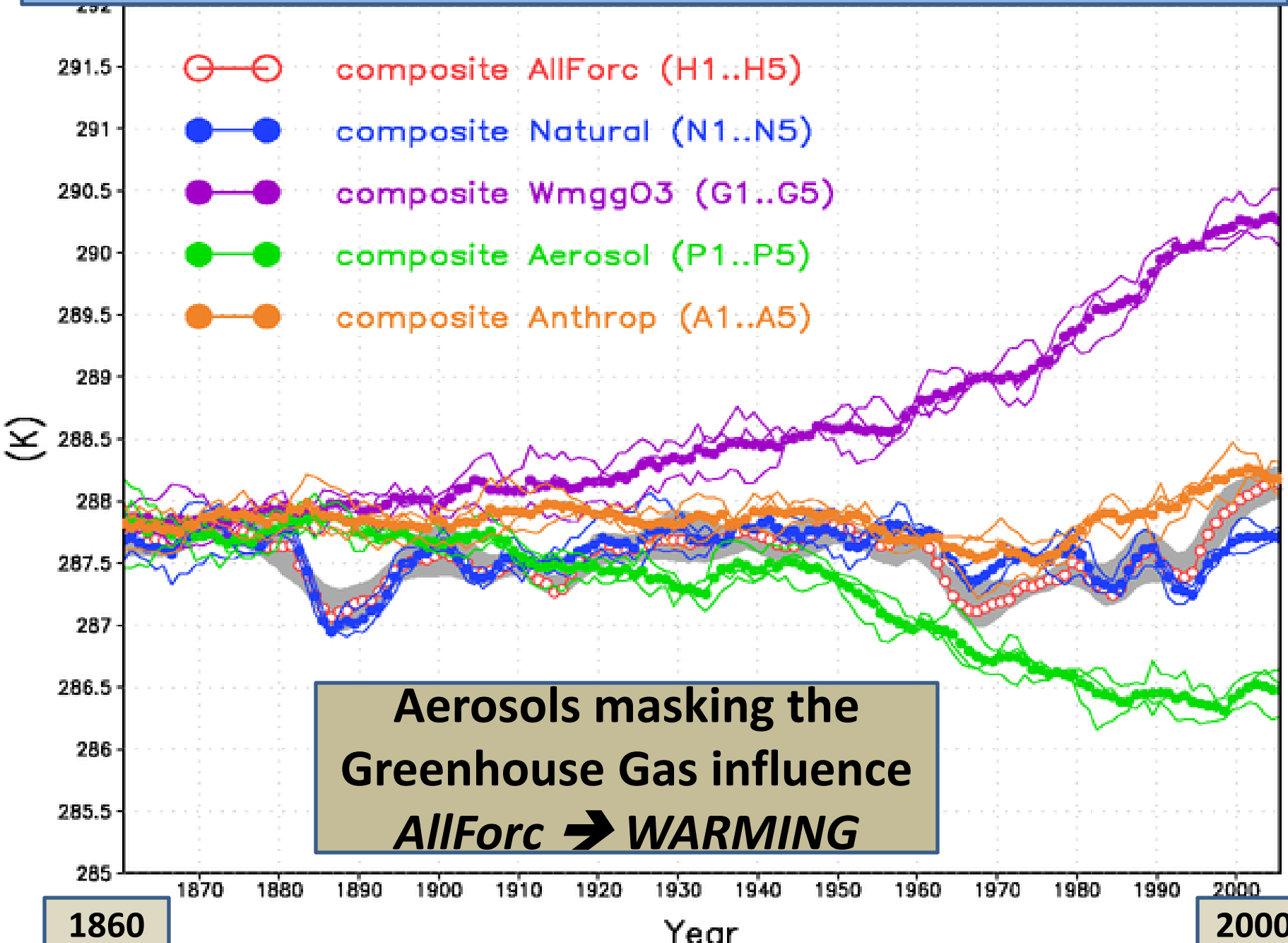
Donner et al., *J. Climate*, 2011

Surface Air Temperature change

[*WMGGO3* ***(warming)*** *and Aerosol* ***(cooling)*** *effects dominant*]



CM3 Simulation: S. ASIA Surface Temperature in the 20th Century

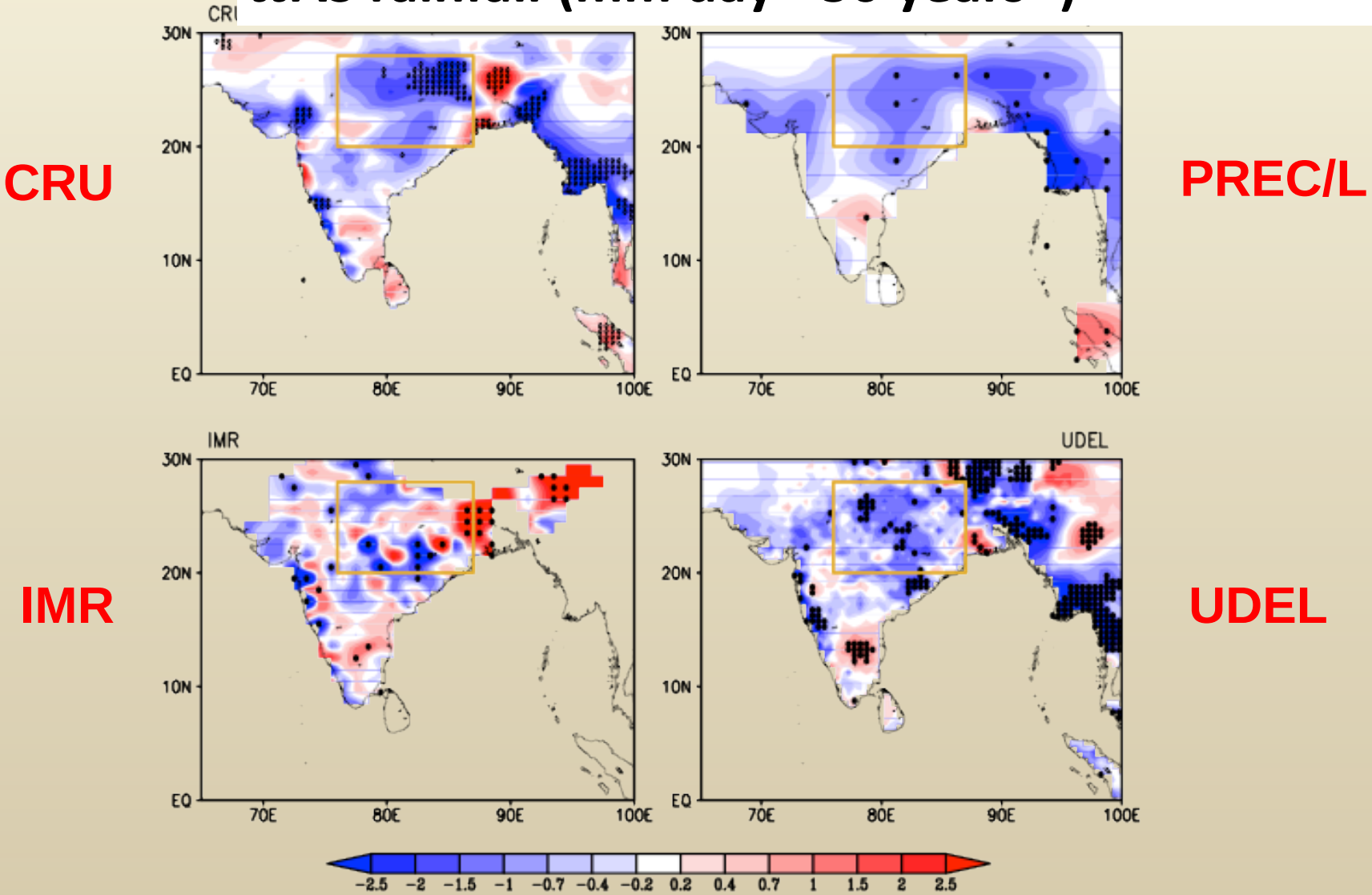


Aerosols masking the Greenhouse Gas influence

AllForc → WARMING

A drying trend over central-northern India during the second half of the 20th century

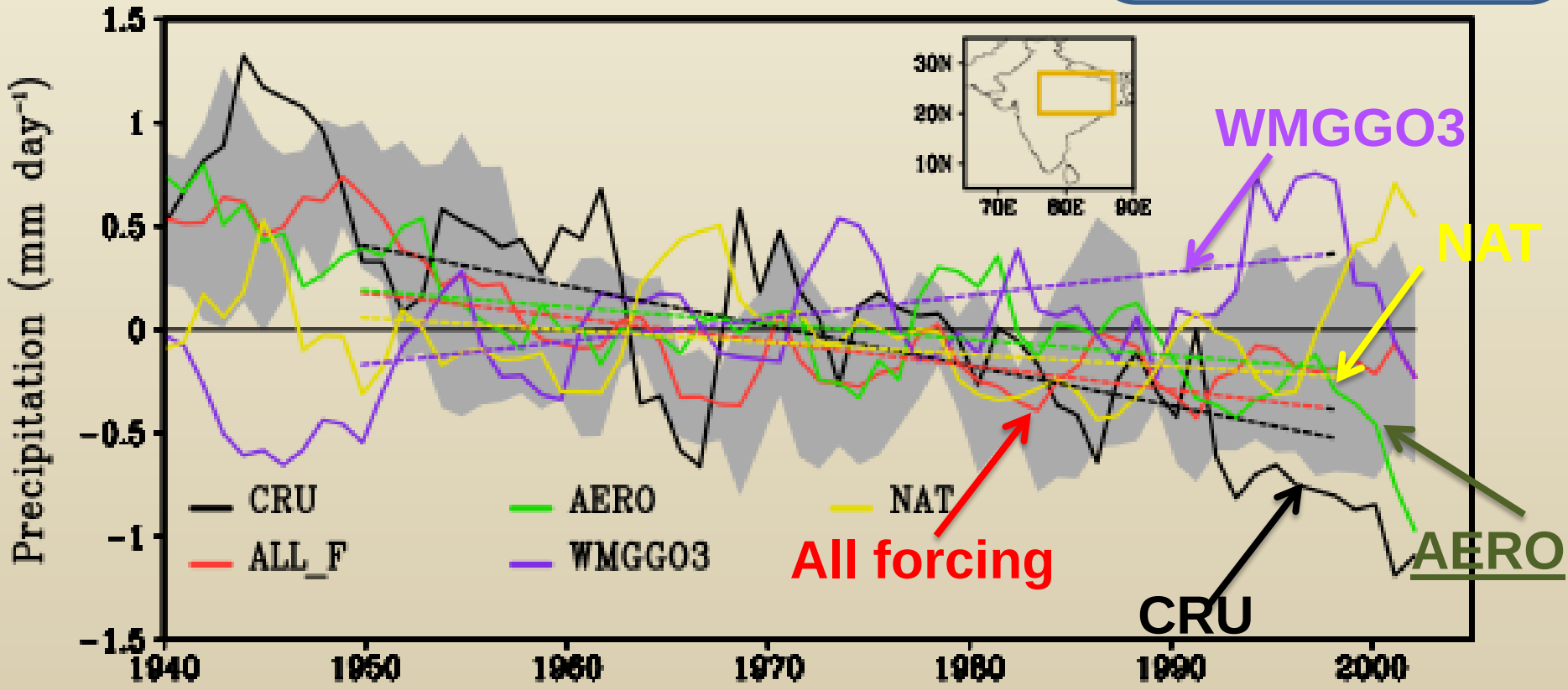
JJAS rainfall (mm day^{-1} 50 years^{-1})



Attribution of the recent trend of the S. Asian summer monsoon using CM3 historical simulations

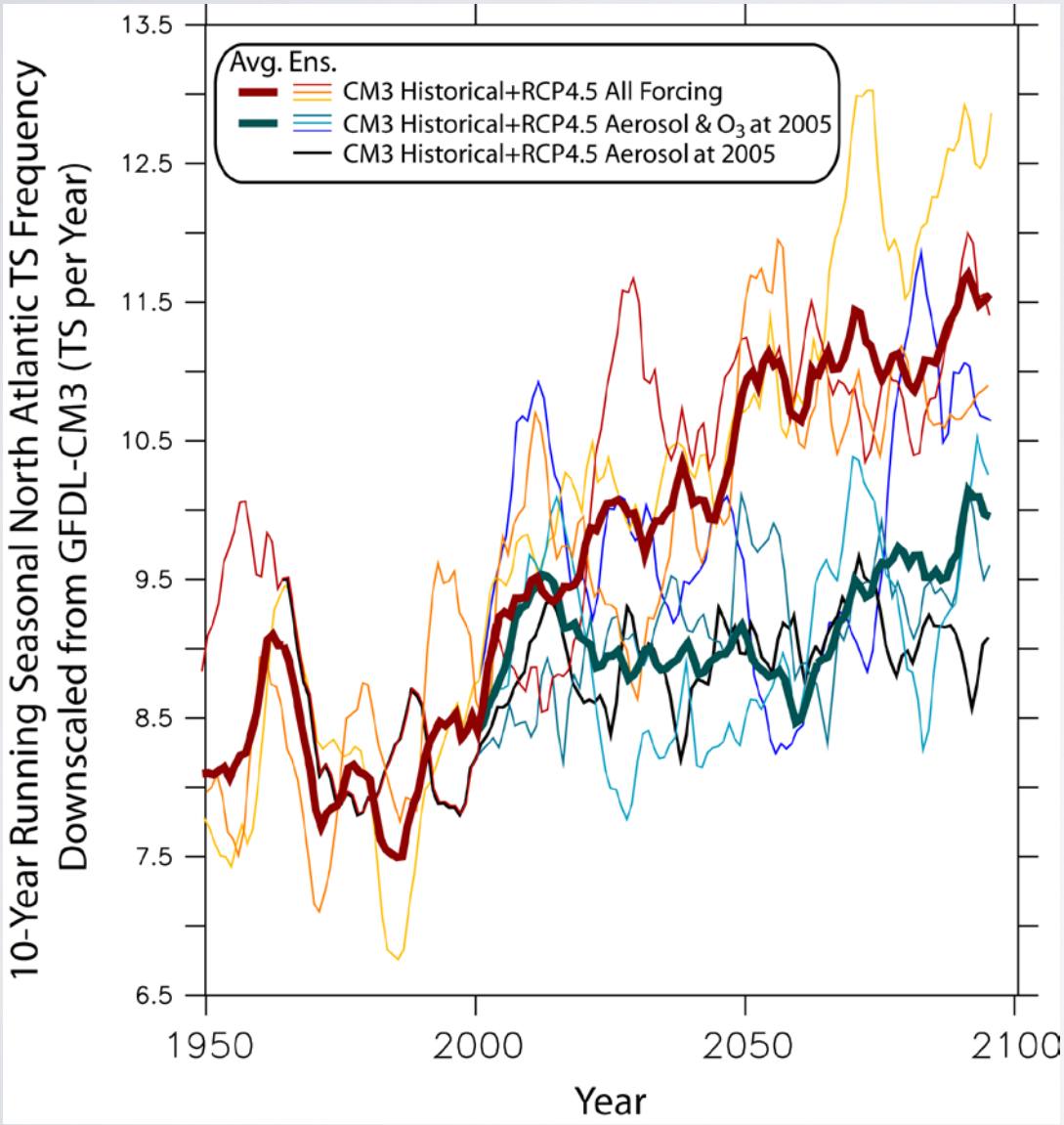
Linear trends of average JJAS rainfall over central-northern Indian (mm day^{-1})

- *AERO trend opposite in sign to WMGGO3*
- *AllForc trend compares well with CRU (Obs)*



Bollasina et al. (Science, 2011)

Aerosols key for NA TS projections
("Cleaning" out aerosols ➔ More storms)



All Forcing

No future aerosol or O_3

No future aerosol

Projected aerosol changes lead to increase in NA TS frequency over 1st half of 21st century

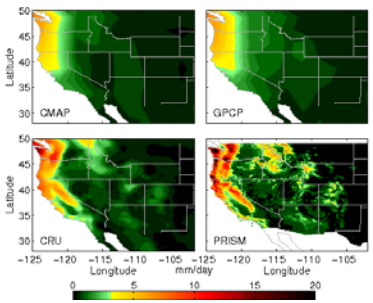
Villarini and Vecchi (2012, Nature C.C.)

Advancing the frontiers with enhanced spatial resolution:

- Atlantic hurricane frequency
- Heat waves
- Intercontinental transport of pollutants (*Global climate and air quality*)

DJF precipitation in Western US

GFDL models vs. PRISM

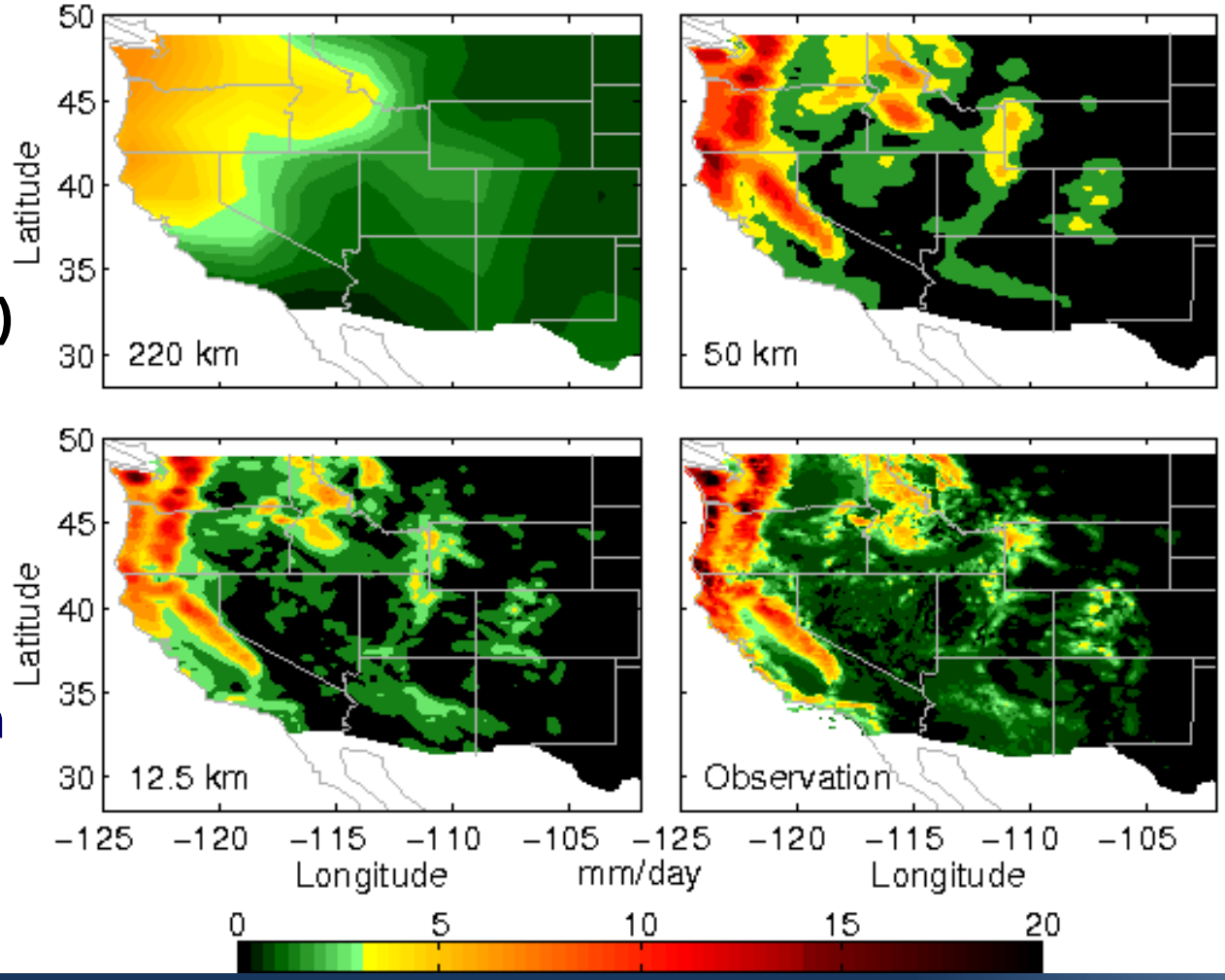


AM2.1 (220 km)

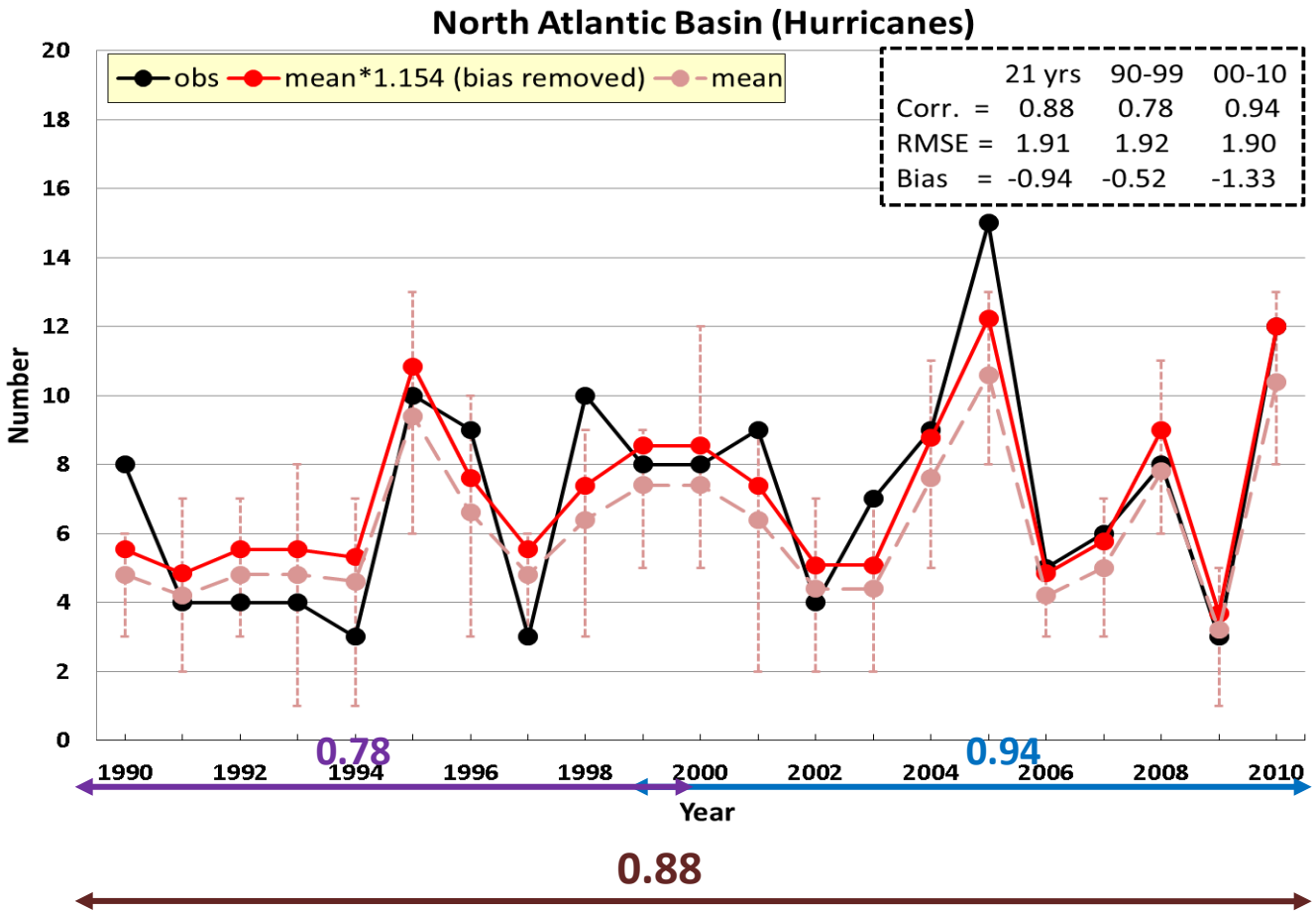
50-km HiRAM

12.5-km HiRAM

PRISM



Retrospective (1990-2010) Seasonal hurricane predictions with GFDL HiRAM



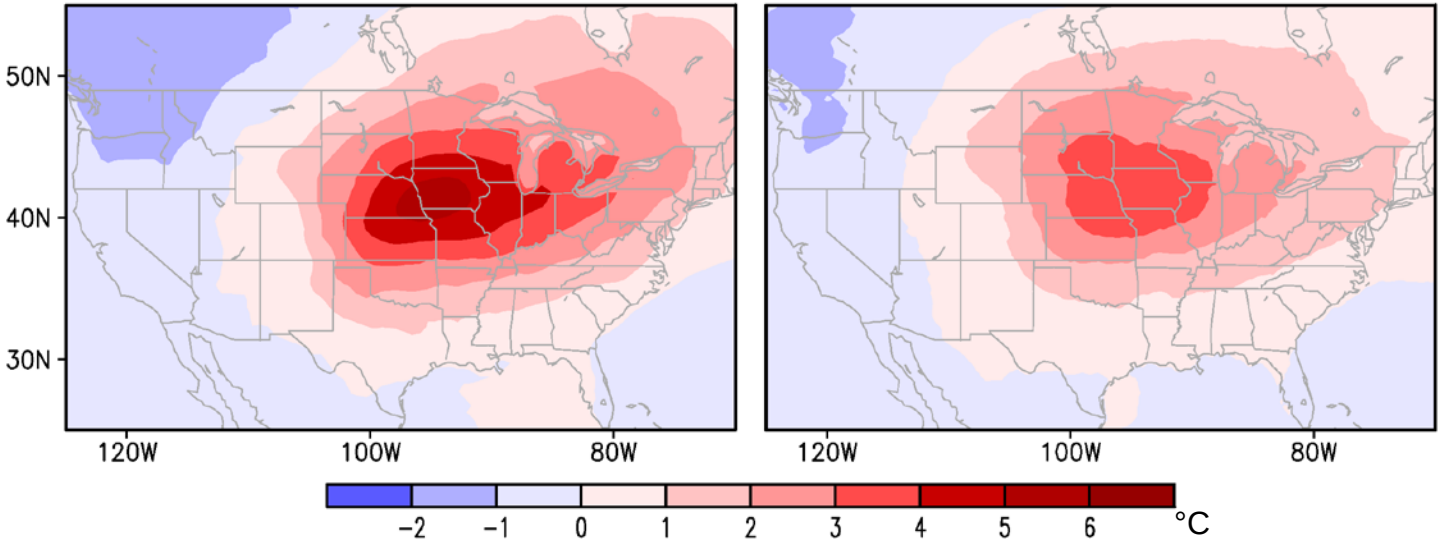
(Chen and Lin 2011, GRL and Chen *and Lin 2012, J. climate)*

Midwest Heat Waves

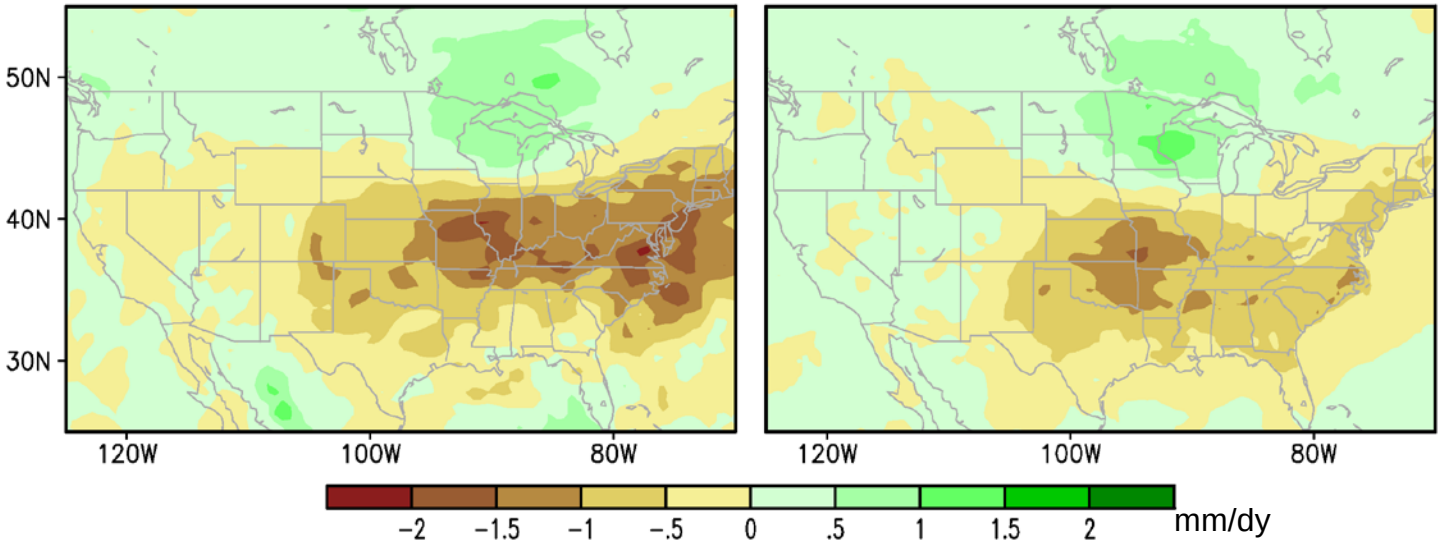
Lau et al. (J. Climate, 2012)

Model Observations

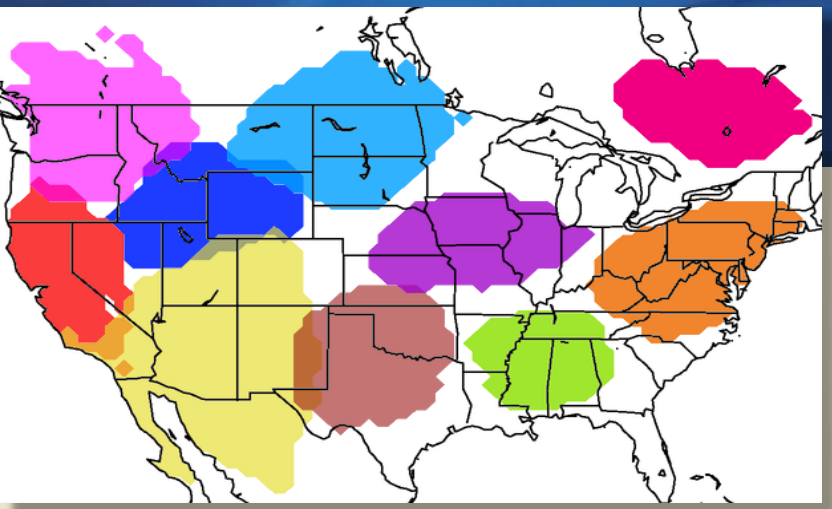
Surface Temperature



Precipitation



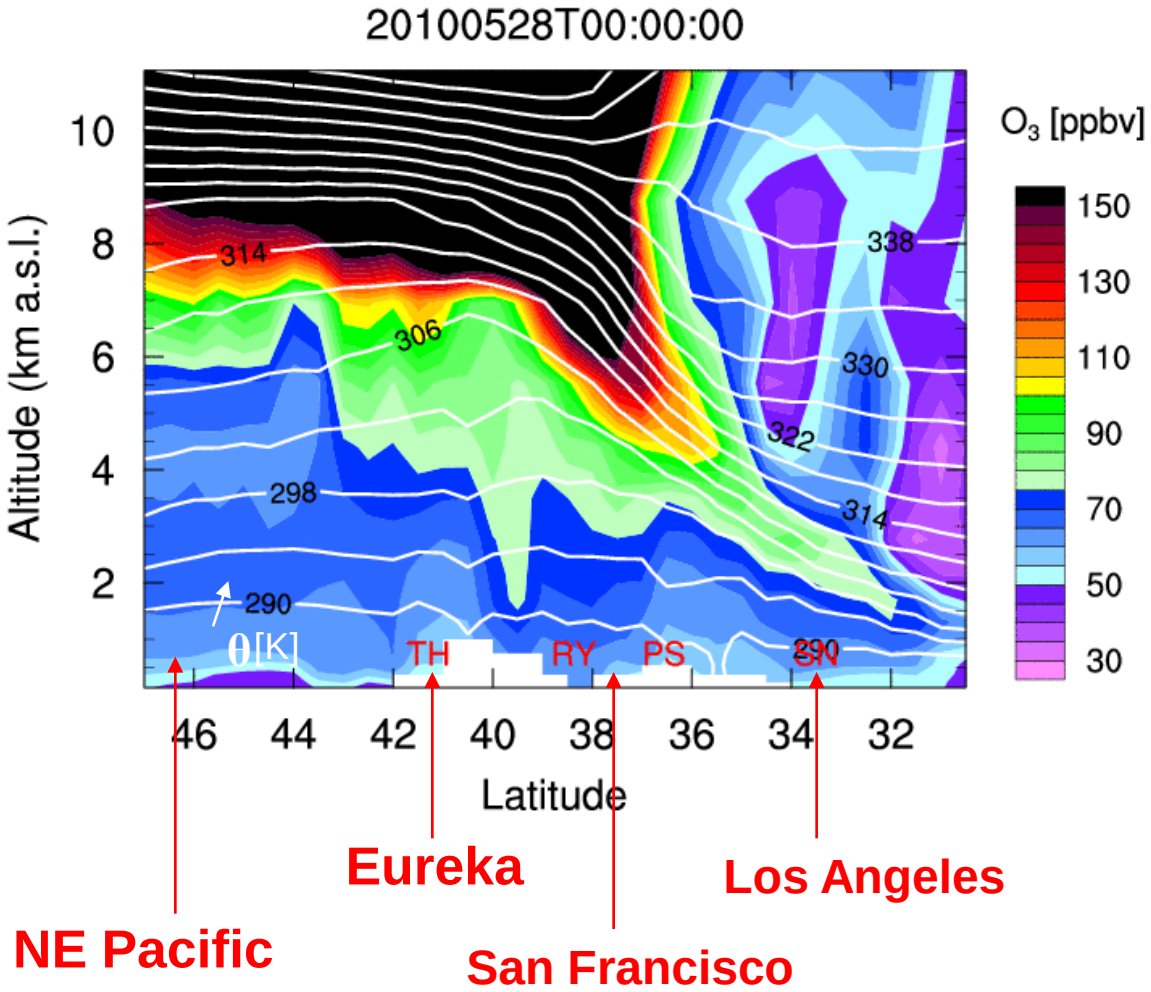
Model Projections
Ratio: 2041-2070 vs 1971-2000



	Duration	# Events/yr	# Heat wave days/yr
Midwest	1.5	2.7	4.0
Northern Plains	1.3	3.8	4.8
Pacific Northwest	1.3	2.4	3.0
SE Canada	1.2	2.5	2.9
Texas-Oklahoma	1.8	2.6	4.5
Mid-Atlantic	1.4	2.7	3.8
California	1.9	2.3	4.3
Gulf Coast	1.2	3.2	4.0
Southwest	2.2	2.9	6.4
Wyoming/Montana/ Idaho	2.2	2.6	5.7

Deep stratospheric ozone intrusions in the new, high-resolution GFDL AM3 model

AM3/C180 simulation of a deep stratospheric O_3 intrusion over California

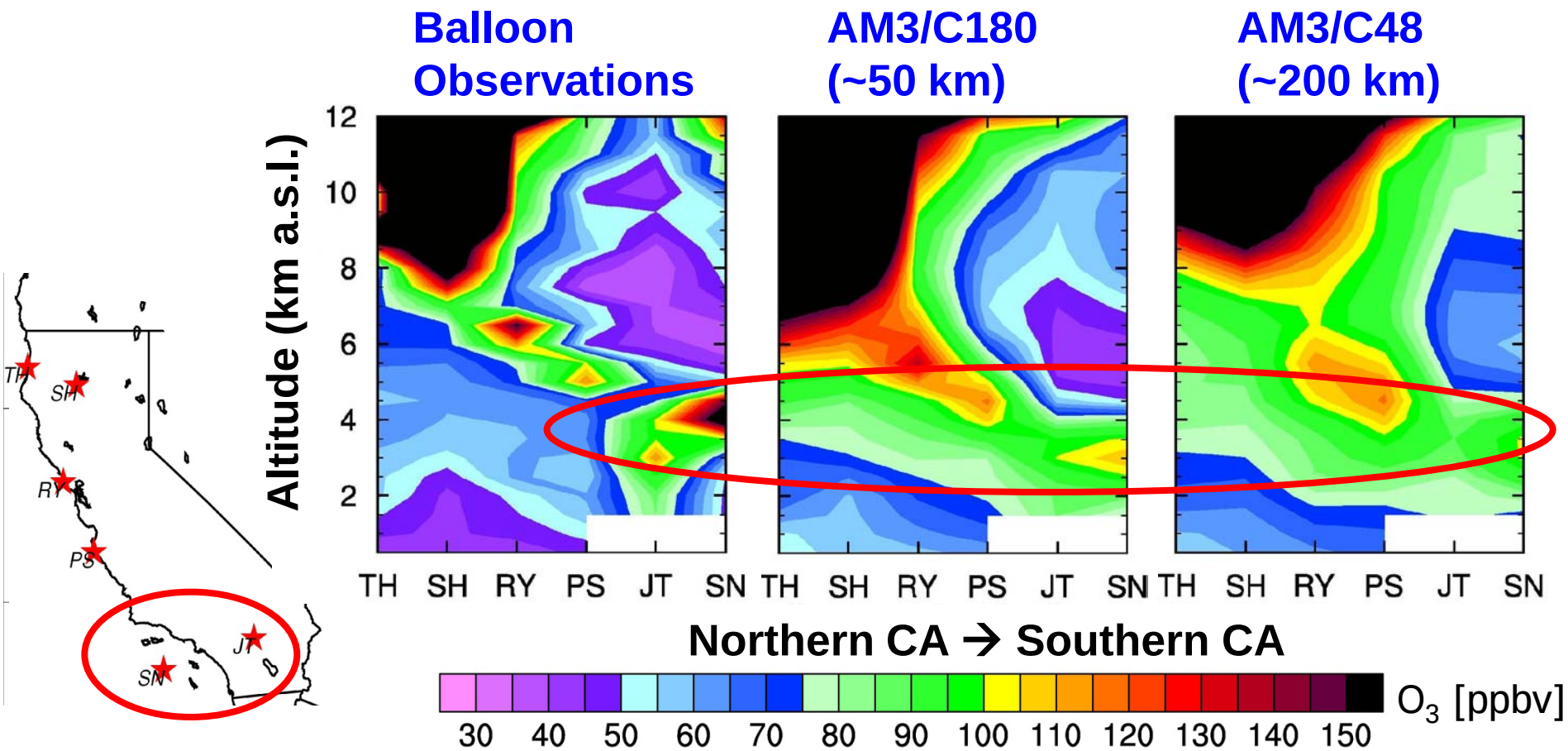


Key model features:

- **C180 horizontal resolution (~50x50 km²)**
- **Full strat & trop chem** [*Donner et al., 2011, J. Climate*]
- **Nudged to NCEP/GFS U and V** [*M. Lin et al., JGR, 2012*]

Extensive evaluation with satellite and *in situ* measurements during NOAA CalNex 2010

Subsidence of stratospheric ozone to the lower troposphere of southern California (May 28, 2010)



- High O_3 (>100 ppbv) just 2-4 km above southern California
- Affecting surface air quality in densely populated regions

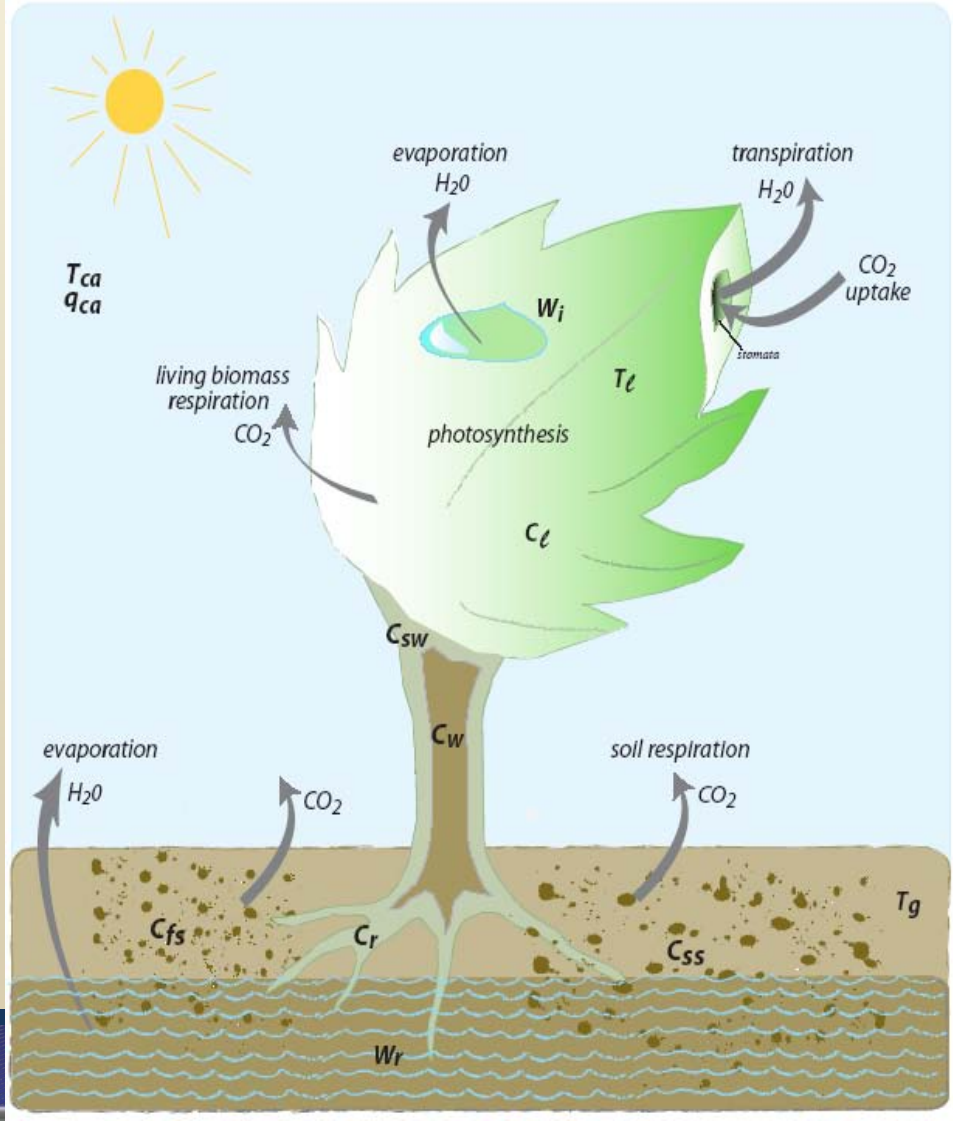
Advancing the frontiers with enhanced representation of Earth System:

- Earth System modeling of carbon-climate interactions
- Marine ecosystems and climate

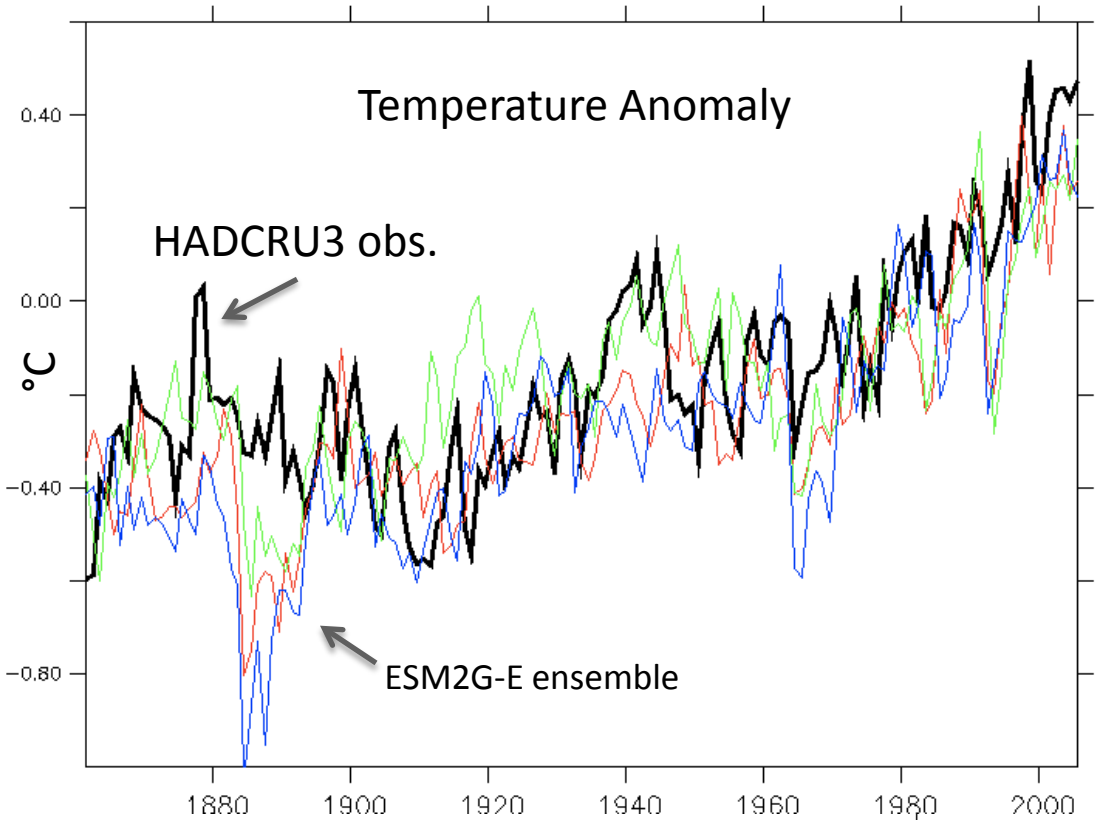
LM2 -> LM3 Land Model [PEI, GFDL, CICS]

- **Dynamic vegetation**
- Subgrid **land-use** heterogeneity
- Distinct treatment of **ground, vegetation, & canopy air**
- **Soil water dynamics** (liquid & frozen)
- Multilayer **snow pack**
- **River network** with capacity for tracers and temperature

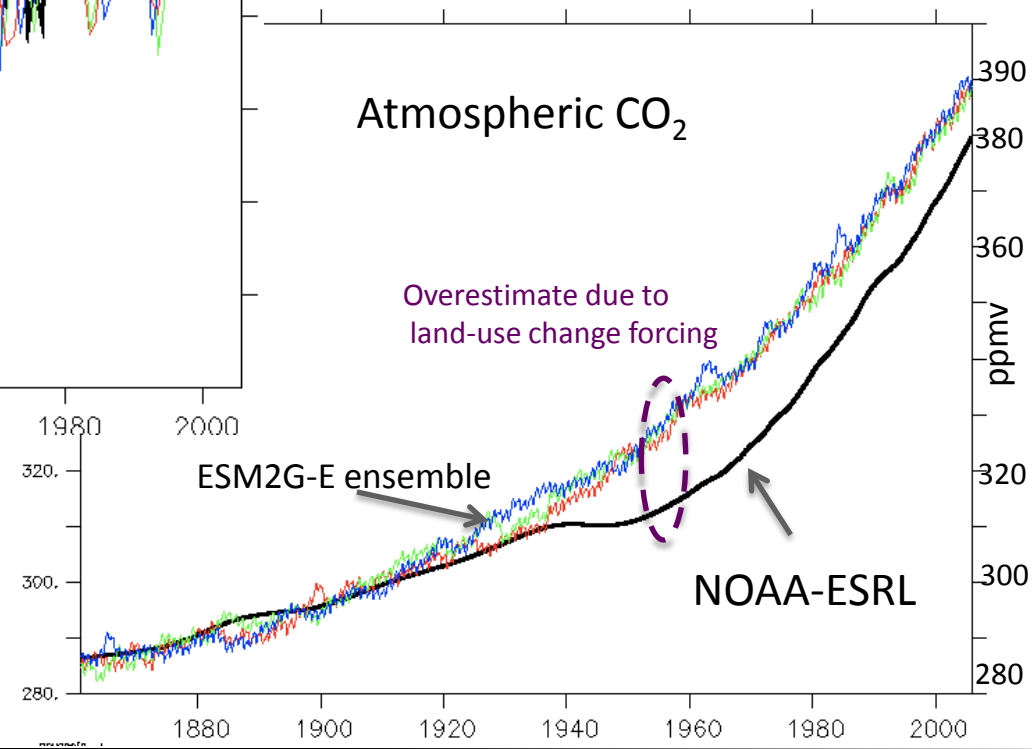
Operate in GFDL's Earth System Models



GFDL ESMs capture historical trends



Drivers:
- CO_2 fossil fuel and cement emissions
- other radiative forcings
- land-use transitions scenario



Shevliakova et al., in prep

Regional case study: climate impacts on eastern Pacific Leatherback turtles

Climate-forced Population Dynamics Model

Land Component:

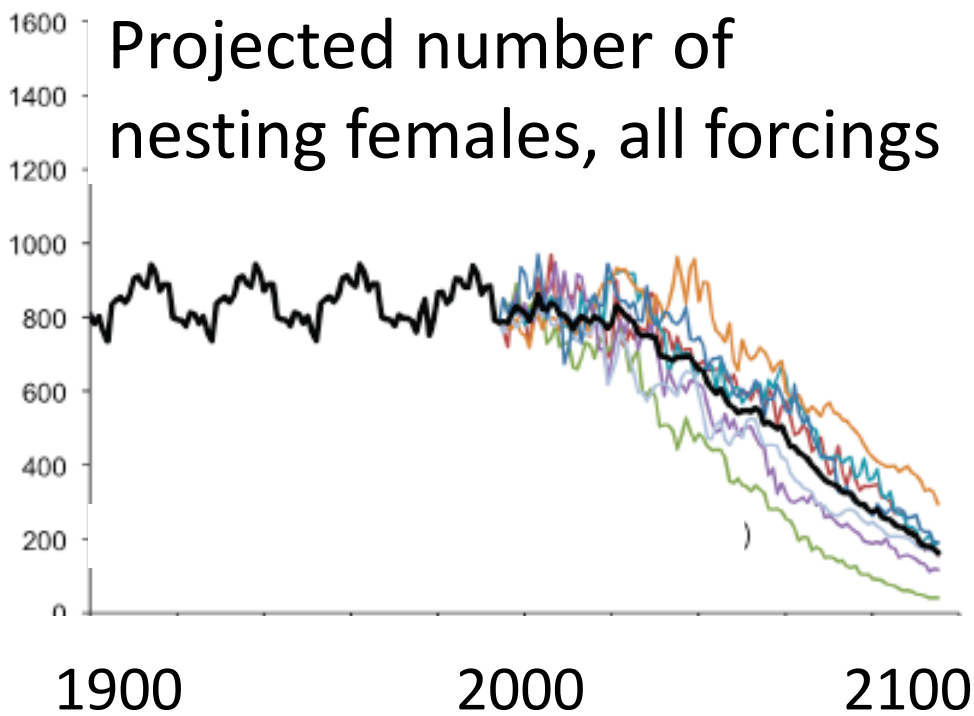
Hatch success = f(SAT,precip)
Emergence success = f(SAT,precip)
Sex ratio = f(precip)

Ocean Component:

Returns = f(Eq. Pac. SST anomaly)
(Proxy for El-Nino driven productivity changes)

Saba et al. (Nature Climate Change, 2012)

Negative climate change impact on endangered eastern Pacific leatherback sea turtles



Saba et al. (Nature Climate Change, 2012)

- Predict declining numbers due to lower hatching and emergence rates with increasing temperatures
- Nesting further north unlikely due to extremely dry conditions in sub-tropics
- Mitigation efforts on beach may be possible if predicted impacts begin to manifest

Advancing the frontiers in science and spatial resolution:

- Seasonal-to-decadal predictability

Decadal prediction: New efforts focused on multi-year/decadal predictions: a mixed initial/boundary value problem

Sources of & Limitations on climate predictability

years to decade

hours to a year

Climatology

(what happens typically, including randomness)

need good observations

Evolution of initial conditions

(e.g., weather or El Niño forecast)

need good observations, models, initialization schemes

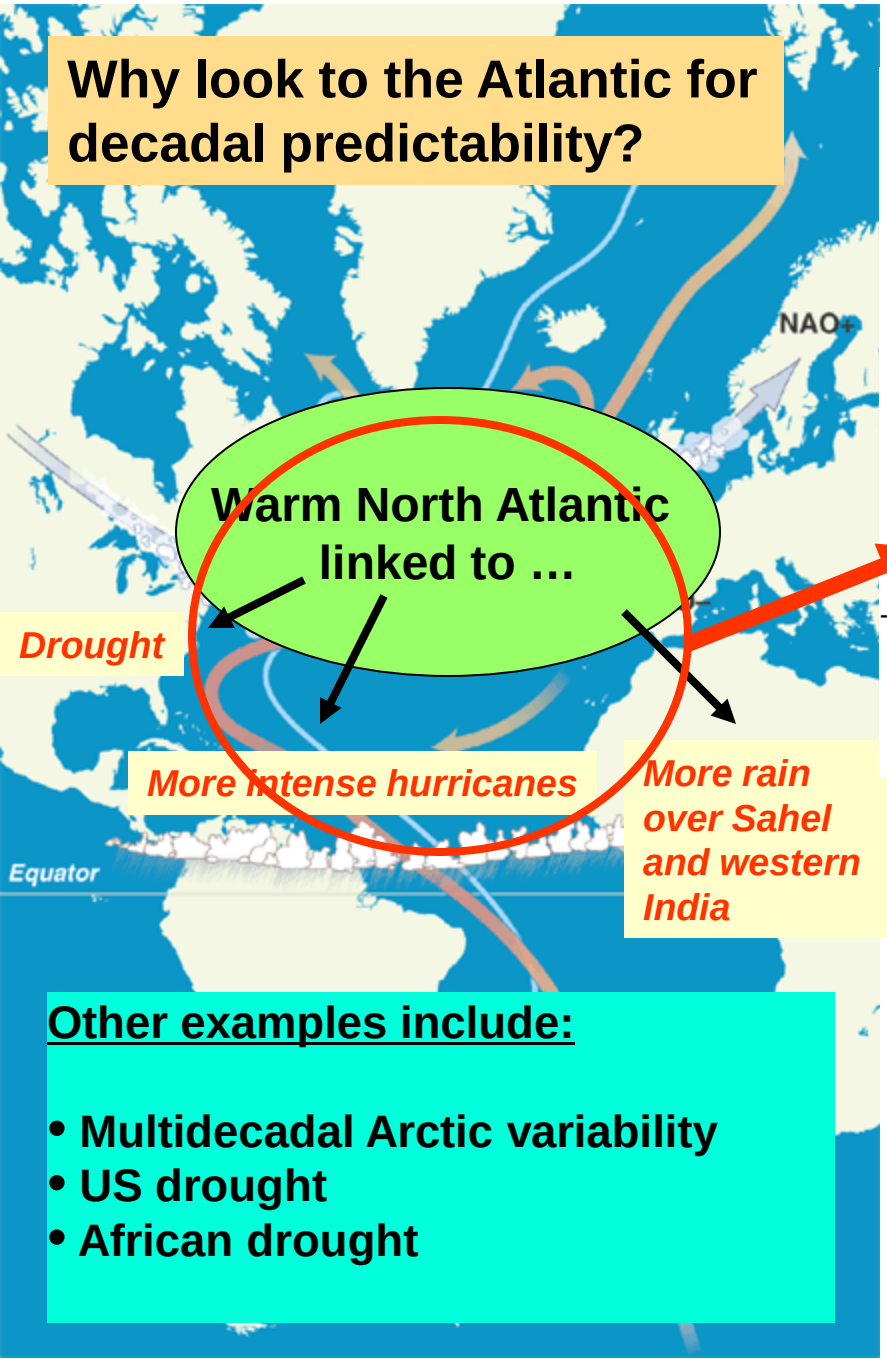
Many decades to centuries

Climate response to forcing

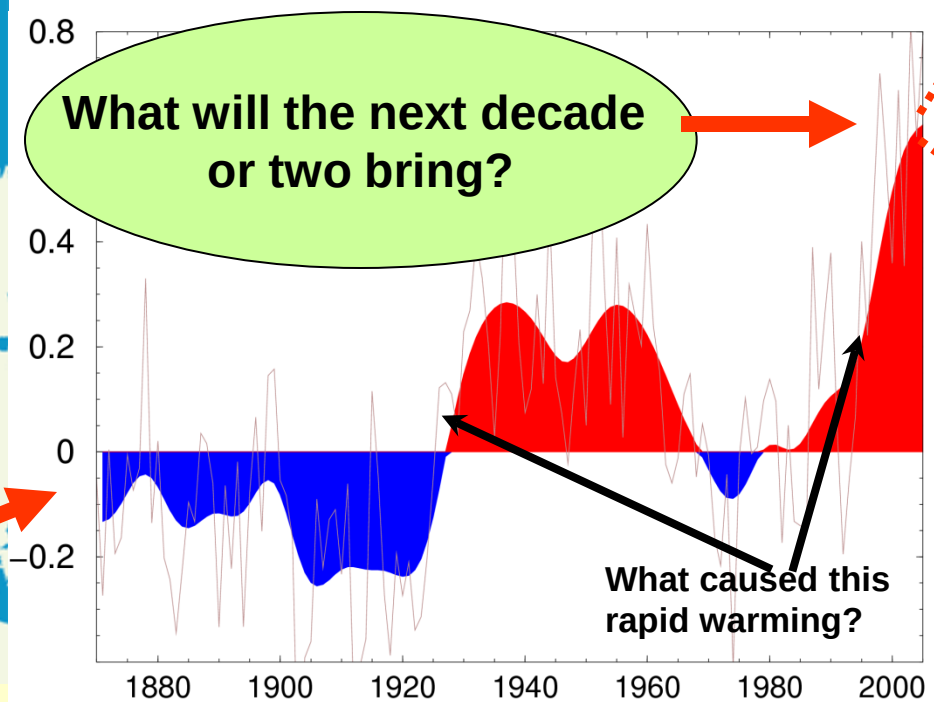
(e.g., CO_2, aerosols, sun, volcanoes)

need good models and estimates of forcing

Why look to the Atlantic for decadal predictability?



North Atlantic Temperature



Other examples include:

- **Multidecadal Arctic variability**
- **US drought**
- **African drought**

Decadal variability:

- ***Significant climate influences***
  - regional to hemispheric
- ***Can phase with longer term warming to cause abrupt change***
- ***Some predictability possible***
- ***Crucial need to attribute observed changes***

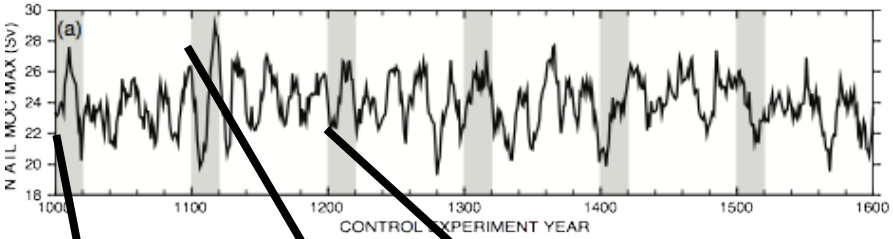
Approaches:

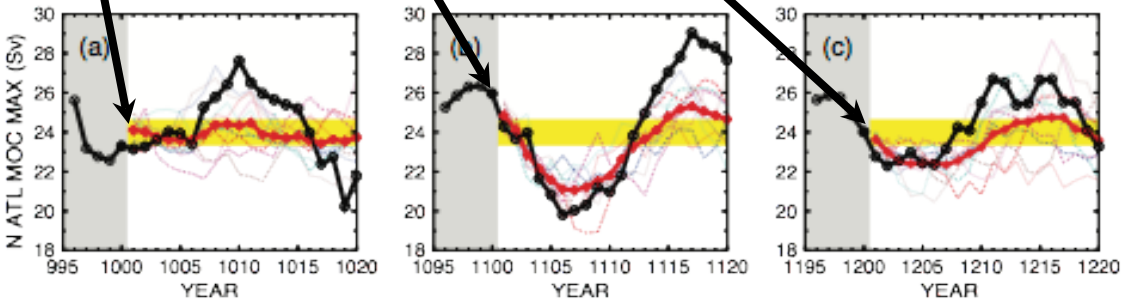
1. Use theory, observations (instrumental and paleo) to improve understanding of decadal variability and its mechanisms

Examples include:

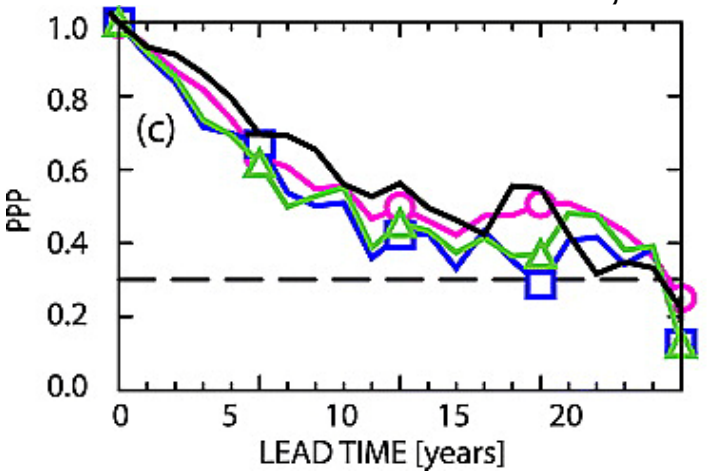
•*Collaboration between GFDL, NCAR and MIT on decadal variability across a hierarchy of models*

•*Collaboration between GFDL, PMEL, Univ Washington, Univ Miami on aspects of simulated and observed Atlantic*





Statistical estimate of predictability
Msadek et al., 2010



These suggest oceanic fluctuations could be predictable a decade in advance

At GFDL, long history of research on prediction systems for seasonal to interannual time scales (ENSO).

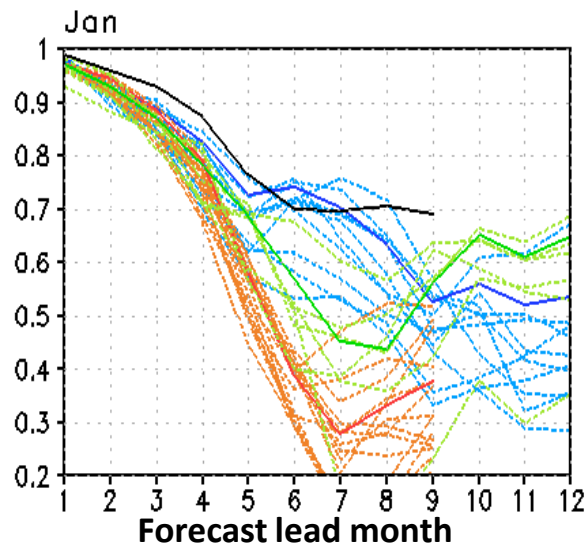
Requires:

- adequate, sustained observing system
- assimilation system to initialize models
- models to make predictions
- conduct large sets of hindcasts to evaluate skill

GFDL research has contributed to NCEP seasonal forecast systems, and is now contributing to a developing national Multi-Model Ensemble (MME).

Preliminary results on forecast skill from MME

ACC of NINO3.4 Index (Jan IC)



NCEP ensemble mean		NCAR ensemble mean	
NCEP members		NCAR members	
GFDL ensemble mean		MME (NCEP+GFDL+CCSM)	
GFDL members			

Courtesy of Tony Rosati

Merge multiple tools and understanding to build experimental long-lead hurricane forecast system: skill from as early as October of year before

April & onward forecasts fed to NOAA Seasonal Outlook Team

Hi-Res AGCM in many different climates. Count storms.

Build statistical model of the response of hurricanes in HiRAM

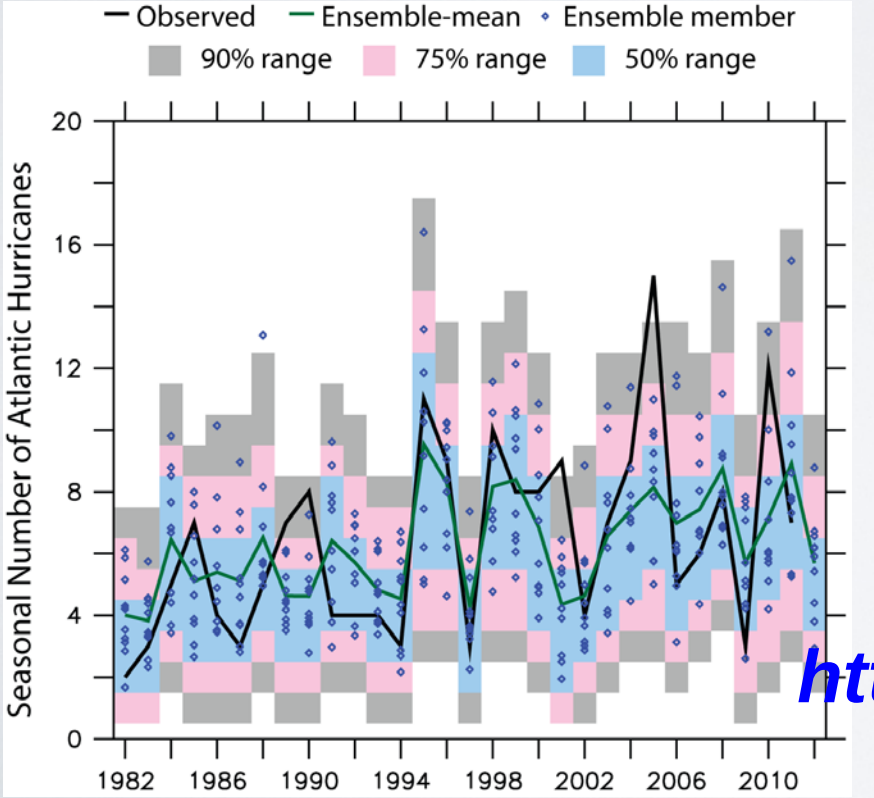
Use initialized coupled model to forecast future values of SST

Apply Stat model to Predicted SST

Make Prediction of Full PDF of Hurricane Activity

HyHuFS

Initialized January: r=0.66



http://gfdl.noaa.gov/HyHuFS

Vecchi et al. (2011, MWR)

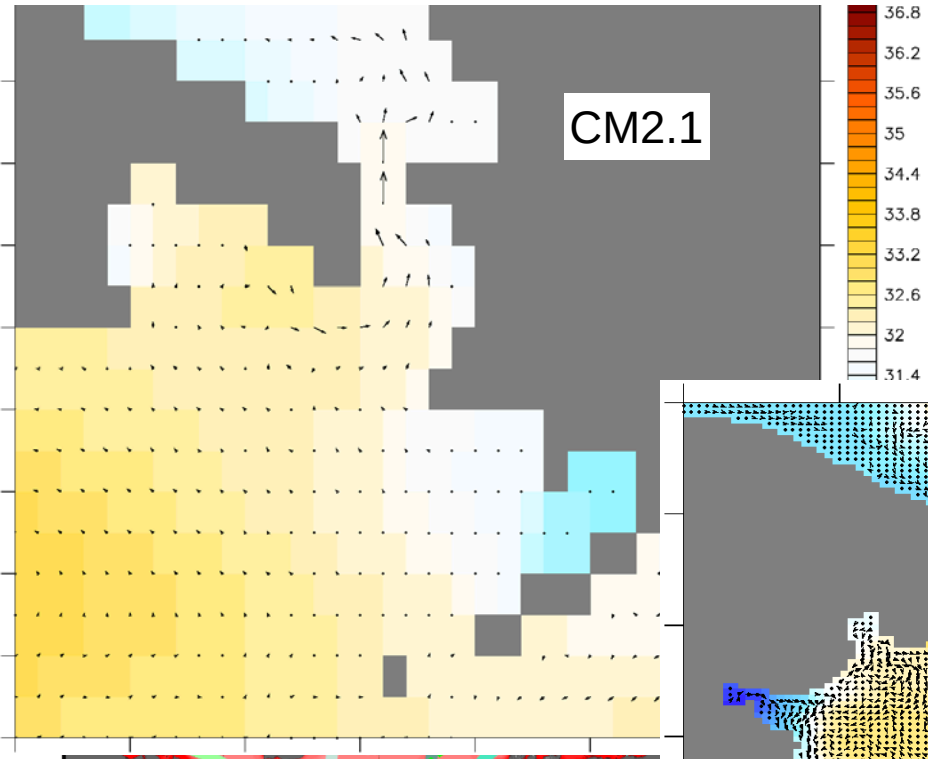
High Resolution Model Development

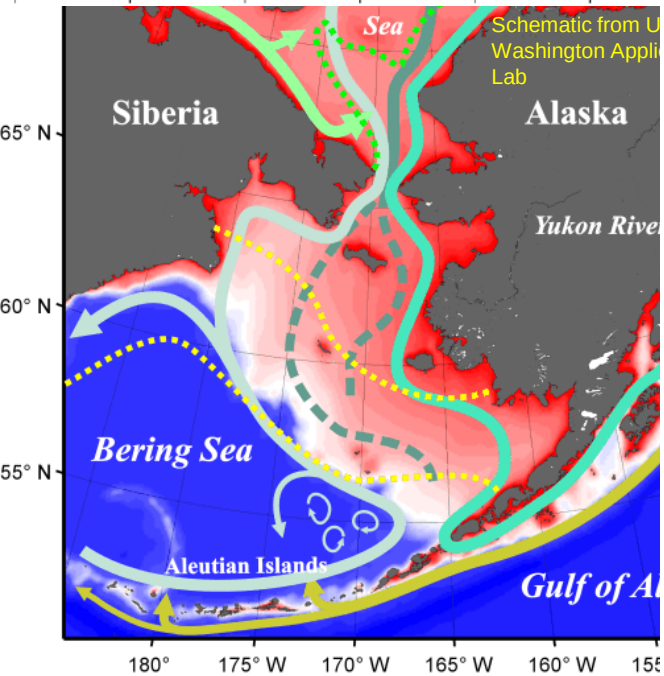
Scientific Goals:

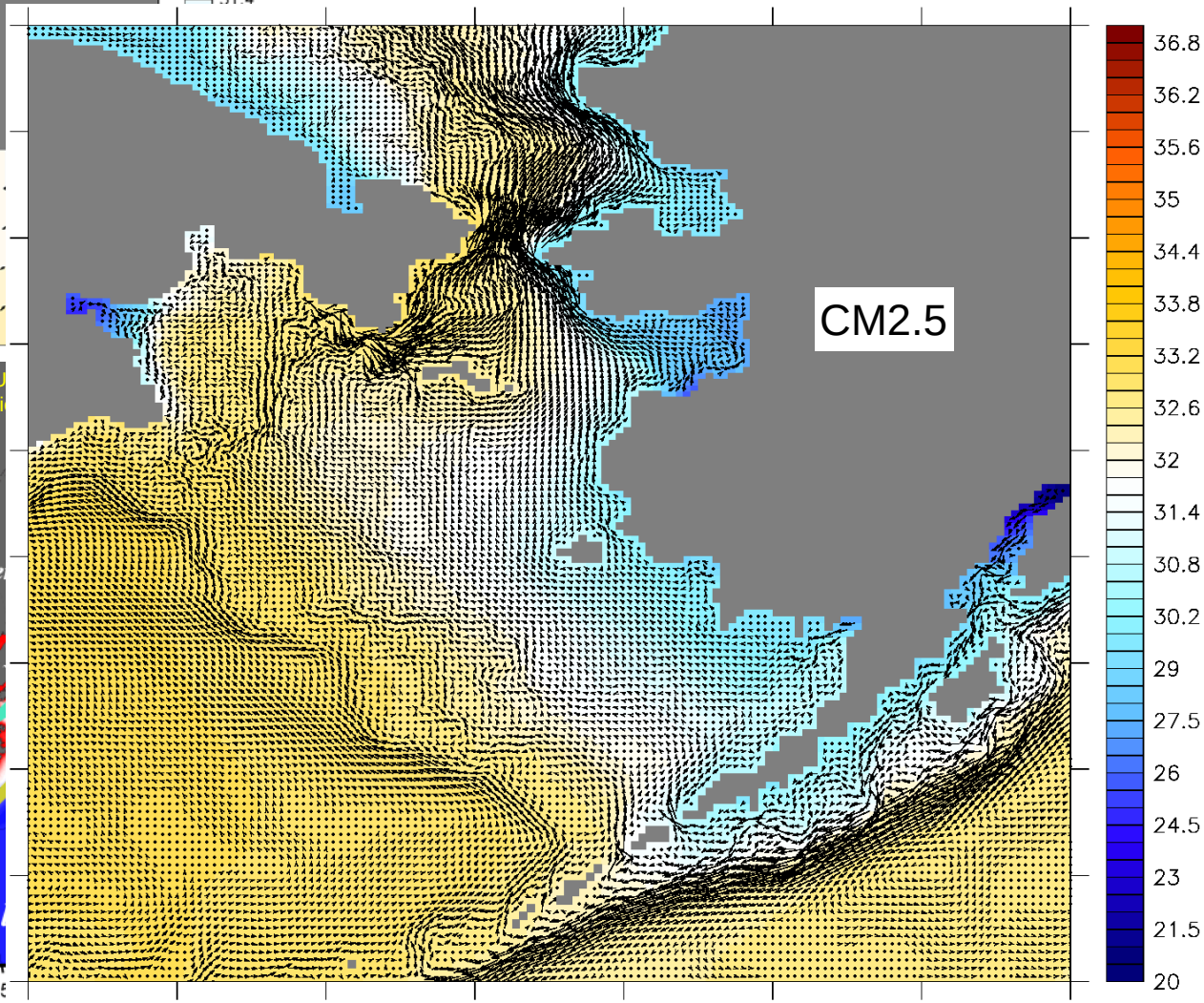
- Developing improved models (higher resolution, improved physics and numerics, reduced bias) for studies of variability and predictability on intra-seasonal to decadal time scales
- Explore impact of atmosphere and ocean on climate variability and change using a high resolution coupled model
- New global coupled models: CM2.4, CM2.5, CM2.6, …

	Ocean	Atmos	Computer	Status
CM2.1	100 Km	250 Km	GFDL	Running
CM2.3	100 Km	100 Km	GFDL	Running
CM2.4	10-25 Km	100 Km	GFDL	Running
CM2.5	10-25 Km	50 Km	GFDL/GAEA	Running
CM2.6	4-10 Km	50 Km	GAEA	Running

Improvement of regional scale circulation
SSS and surface currents







- Robust predictions will require **sound theoretical understanding** of decadal-scale climate processes and phenomena.

- Assessment of predictability and its climatic relevance **may have significant model dependence**, and thus may evolve over time (with implications for observing and initialization systems).

But … even if decadal fluctuations have limited predictability, it is still important to better understand them to aid in the interpretation of observed climate change.

Strategy to accomplish the NOAA Climate Goal objectives [*from the GFDL 5-10 year Strategic Science Plan, June 2011*]

Through comprehensive numerical modeling ,

➔ Understand the processes, interactions and mechanism governing the climate and Earth System

➔ Estimate climate forcings, sensitivities and variability

➔ Goal of making accurate predictions and reliable projections

- Basic climate processes and their representations in models
- Comprehensive modeling of climate system variability and change
- Detection and attribution, and predictions of extreme events
- Detection and attribution, and predictability of modes of climate variability
- Ocean processes in climate
- Cryospheric amplification of climate change and sea-level rise
- Understanding the Earth System including biosphere and human activities
- Climate science, and links to impacts

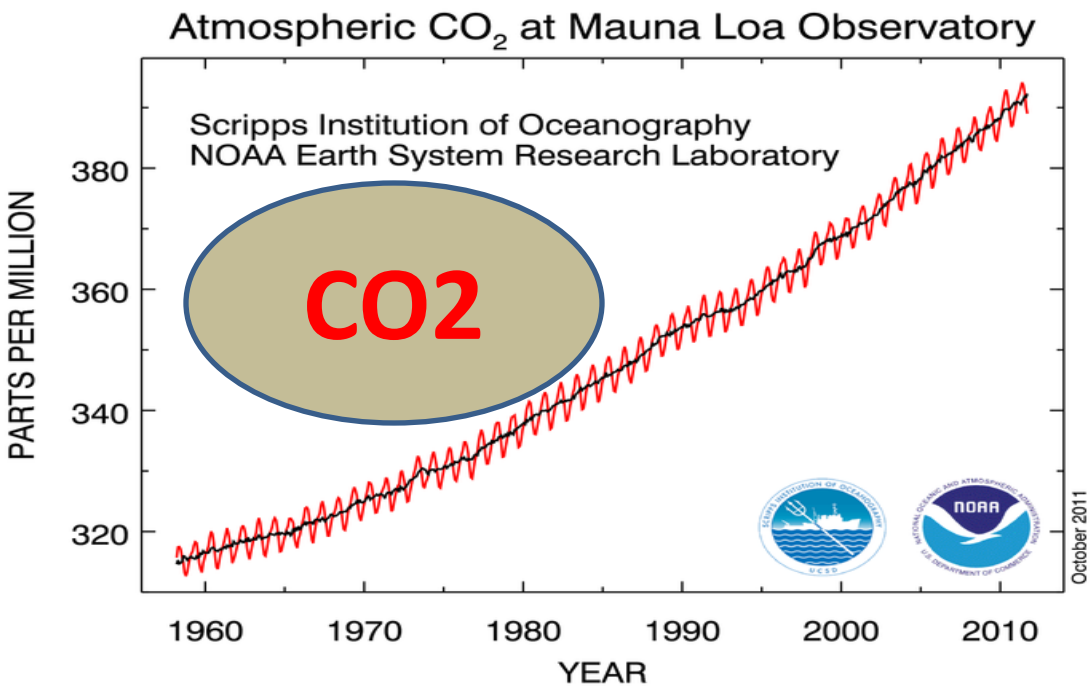
Longer-term research outlook [10 years]

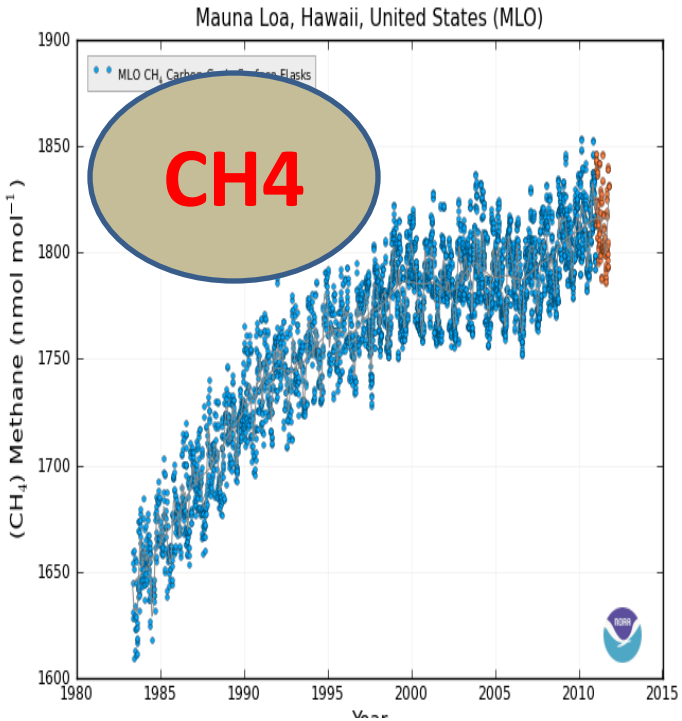
- Higher spatial resolution and increased physical realism in models
- Accounting for the system complexity; process understanding
- Hydrologic cycle: the regional-to-local aspects
- Short-lived species – emissions, transport, deposition
- Aerosol-cloud-climate feedbacks ; influences on precipitation
- Tropical storm simulations
- Land-ice and cryospheric modeling; polar (Arctic and Antarctic) climate variations and trends
- Decadal Predictability: anthropogenic forcing, natural variability
- Extremes and abrupt climate change on different timescales
- Biosphere-atmosphere-cryosphere-climate interactions (CO2, methane, and other greenhouse gases; dust, soot)
- Biogeochemical cycles, and the exchanges of carbon between atmosphere, ocean and land
- Climate change impacts on sea-level rise and ecosystems

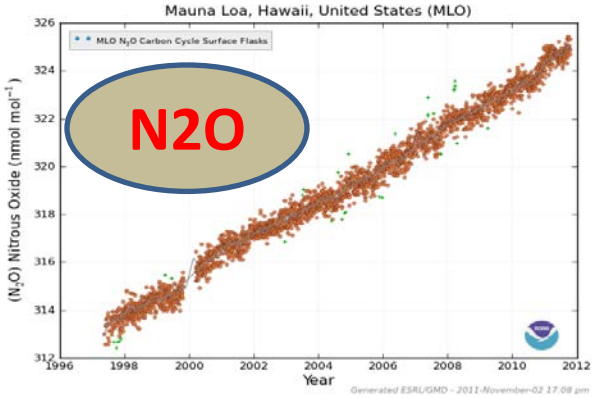
The END

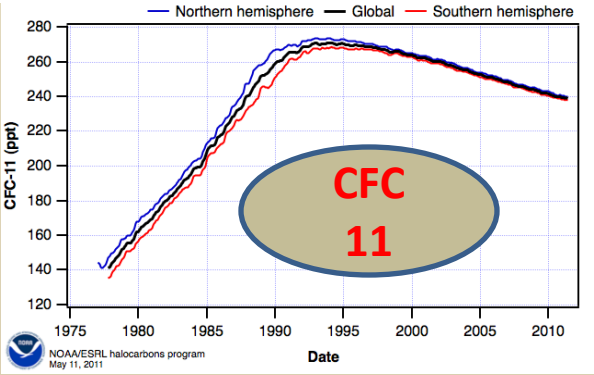
Thank you for your attention !

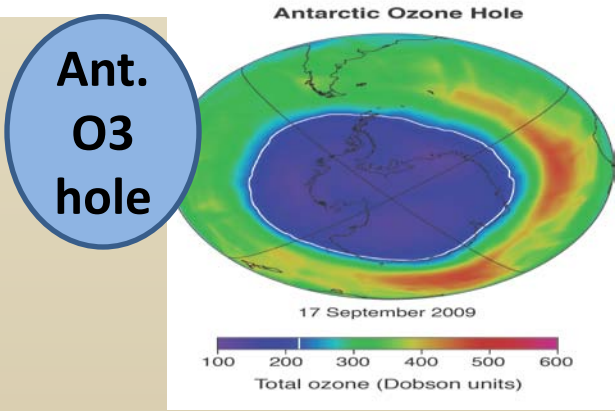
Human-influenced Greenhouse Gas Forcing Agents











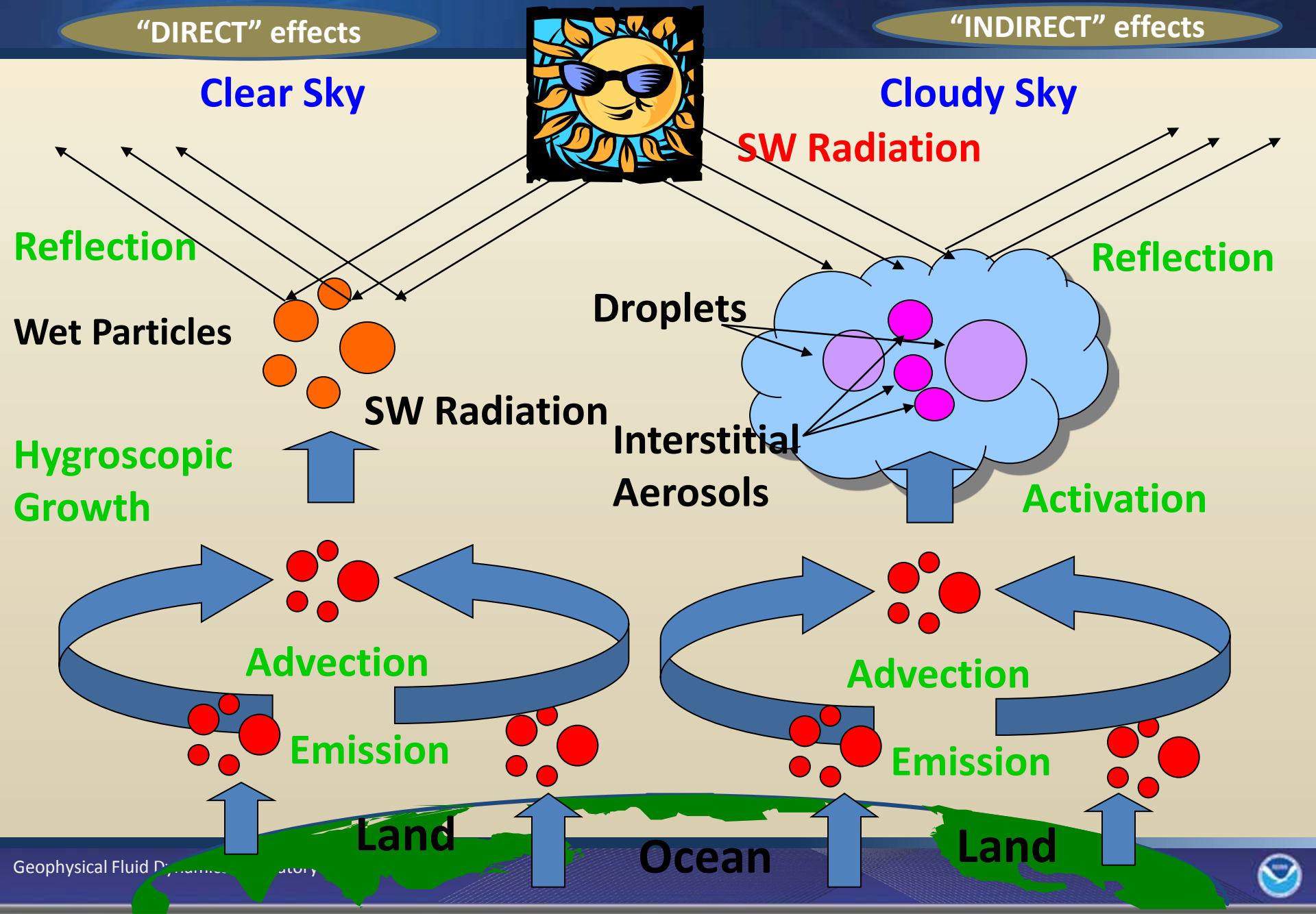
Courtesy: NOAA/ GMD; WMO/UNEP 2010

The World of Aerosols [Sulfate, BC, OC,……]

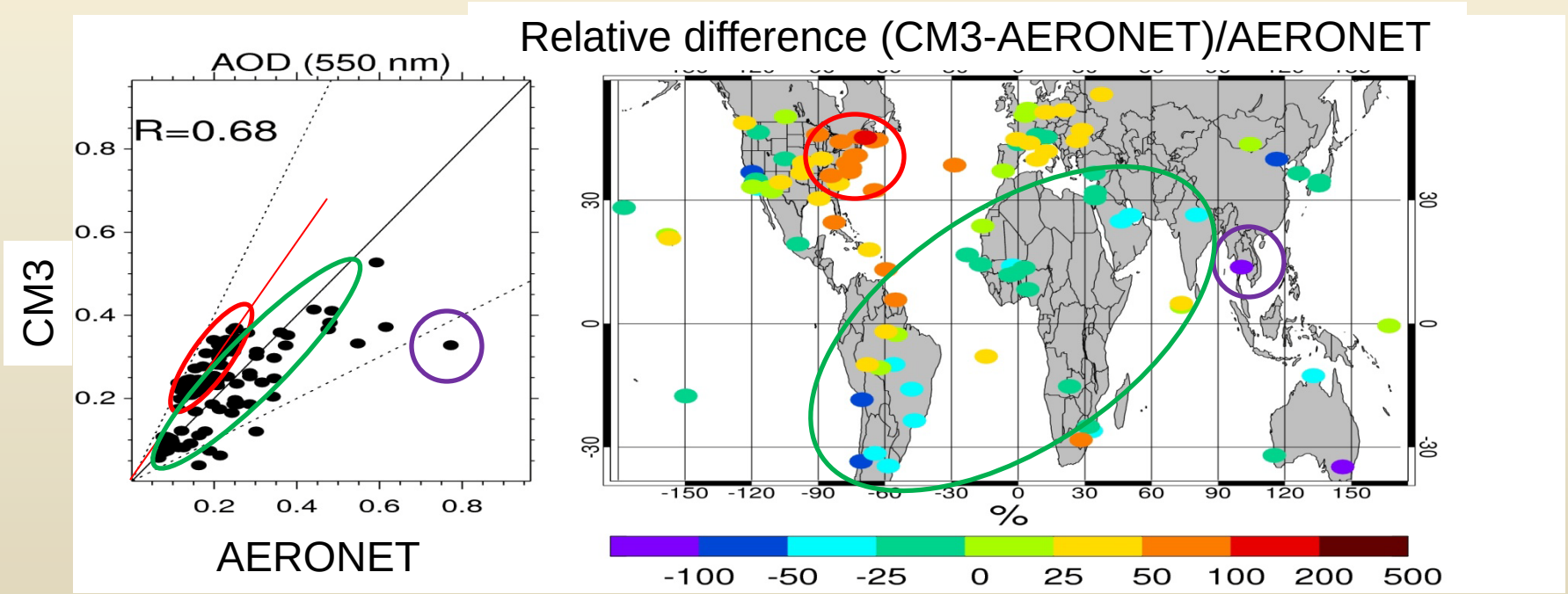
Many human-influenced factors

Courtesy: NOAA Fact Sheet (Ravishankara et al., 2011)

Aerosol-Cloud-Climate Interactions



Comparison CM3 AOD with sunphotometers

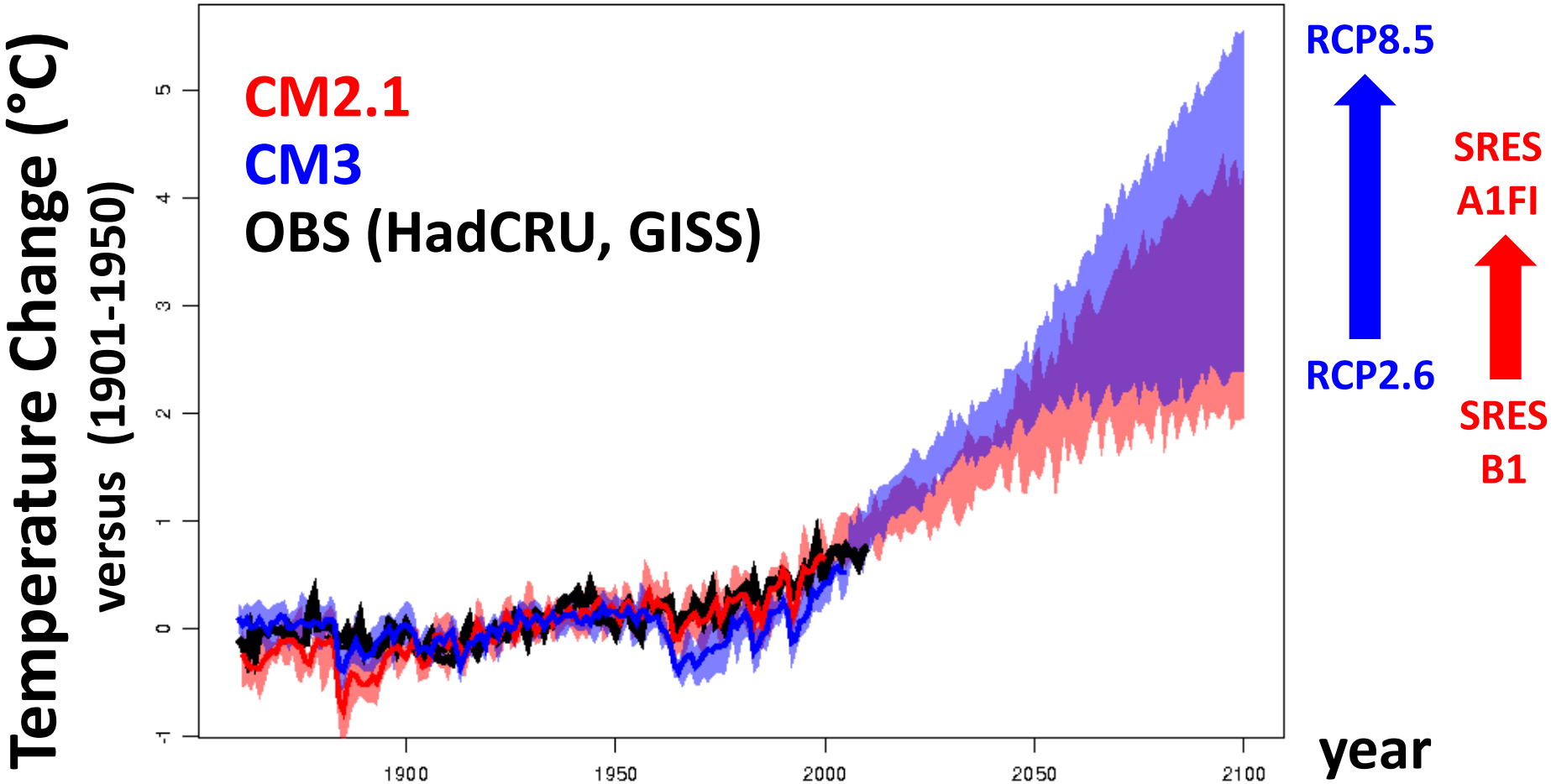


CM3 < 1.5 AERONET in US East coast

CM3 ~ AERONET in biomass burning, dusty regions, India

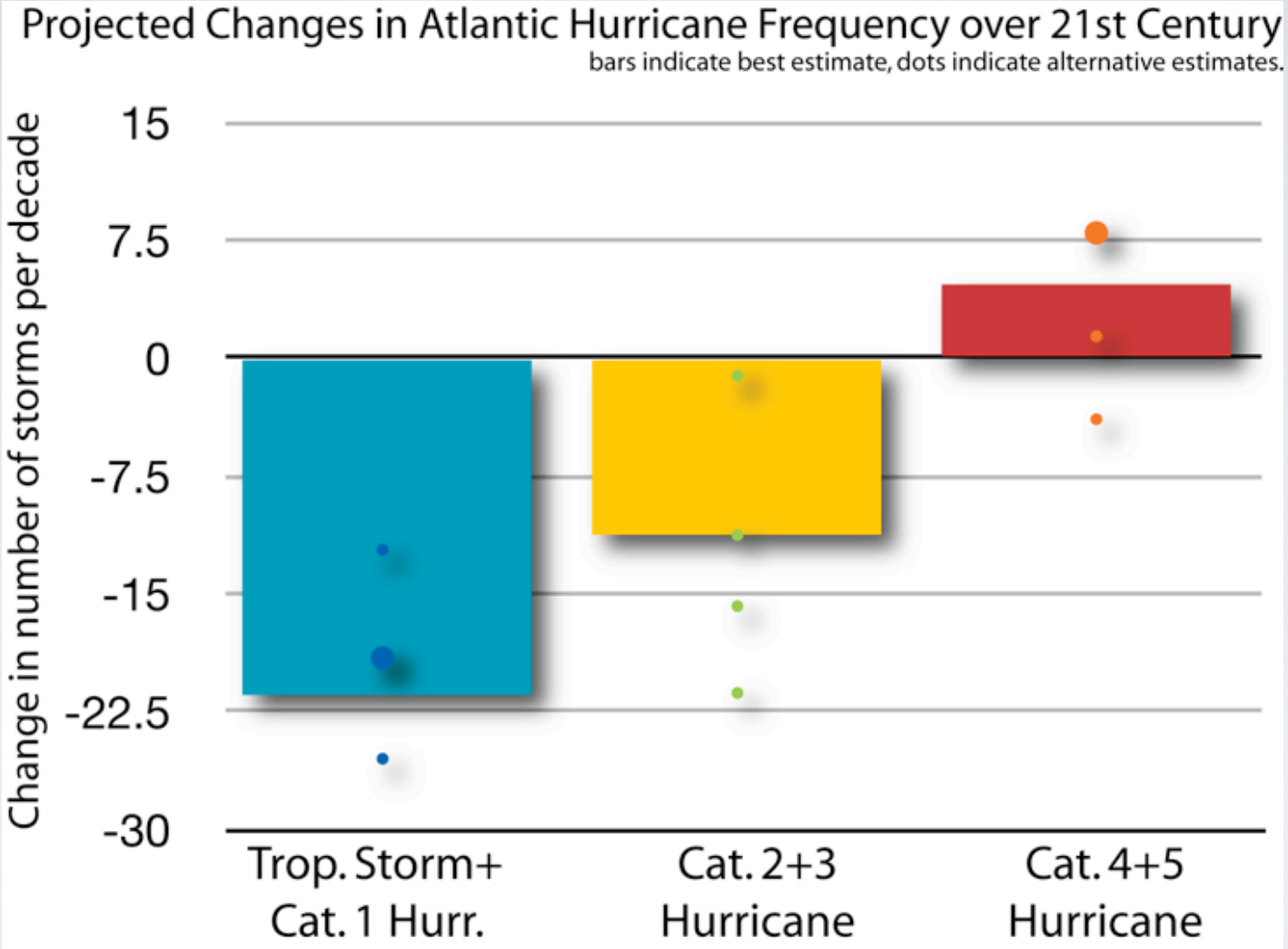
CM3 < 2 over Mega-cities (e.g. Bangkok)

Surface Air Temperature



Greater 21st century warming projected by CM3/RCP than CM2.1/SRES

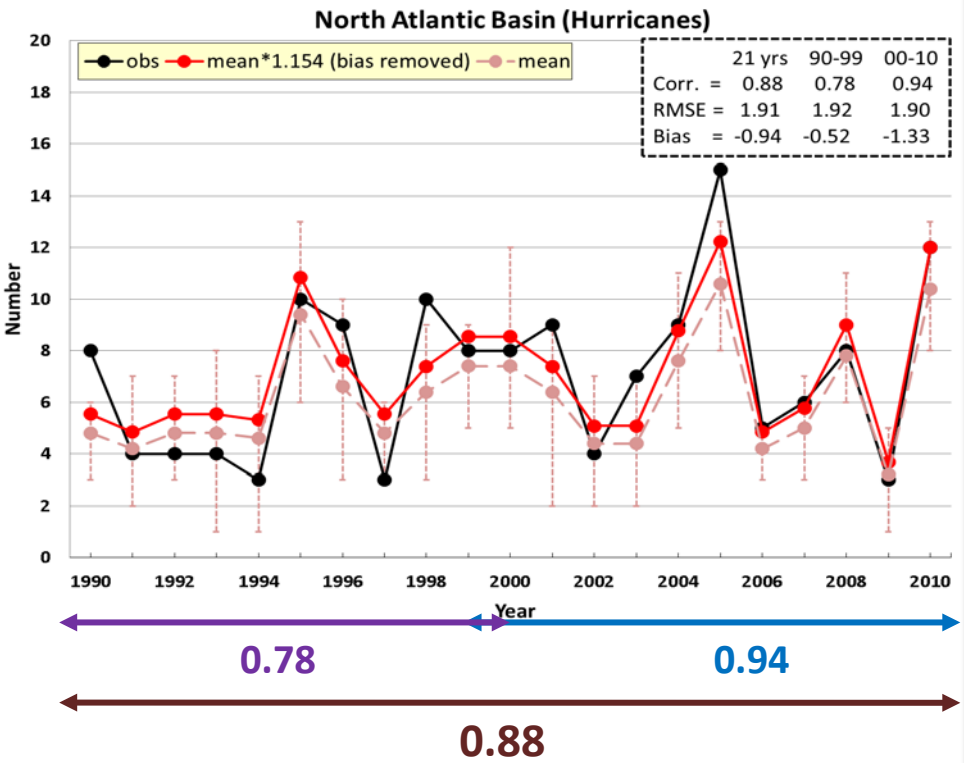
For Atlantic: Overall frequency decrease projected, but more of the strongest storms



Adapted from Bender et al (2010, Science)
see also Knutson et al. (2008, Nature Geosci.)

Retrospective Atlantic hurricane predictions

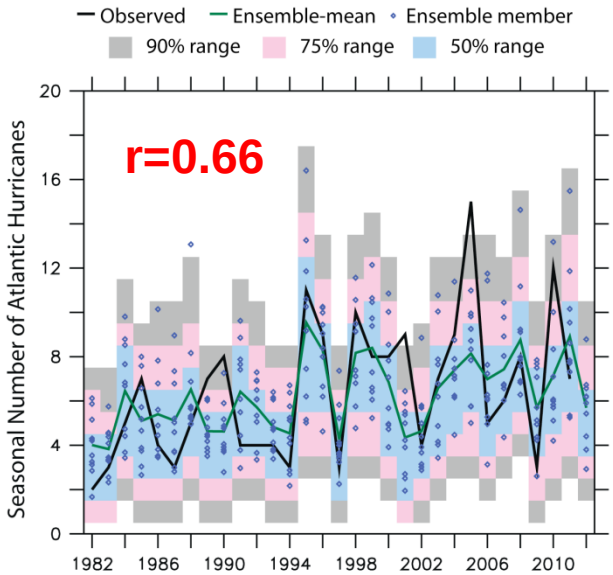
Seasonal with GFDL HiRAM
Initialized 1-July
(1990-2010)



(Chen and Lin 2011, GRL and Chen *and Lin 2012, J. climate)*

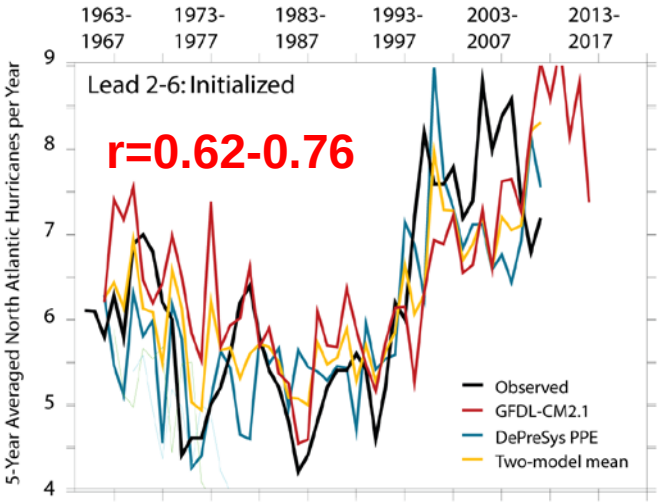
GFDL HyHUFS:
Seasonal Init. 1-January (1982-2012)

(Vecchi *et al.* 2011, *MWR*)



Multi-year 2-6 Year lead (1962-2012)

(Vecchi *et al.* 2012, *J. Clim.*)

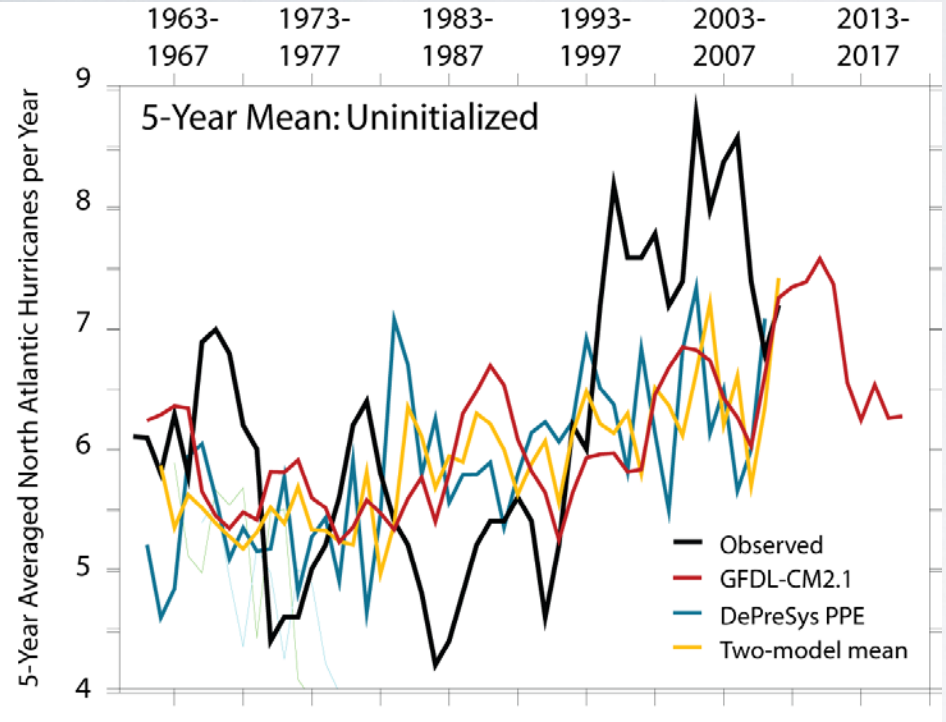


http://www.gfdl.noaa.gov/hyhufs

Experimental decadal predictions

Hybrid system: statistical hurricanes, dynamical decadal climate forecasts

FORCED



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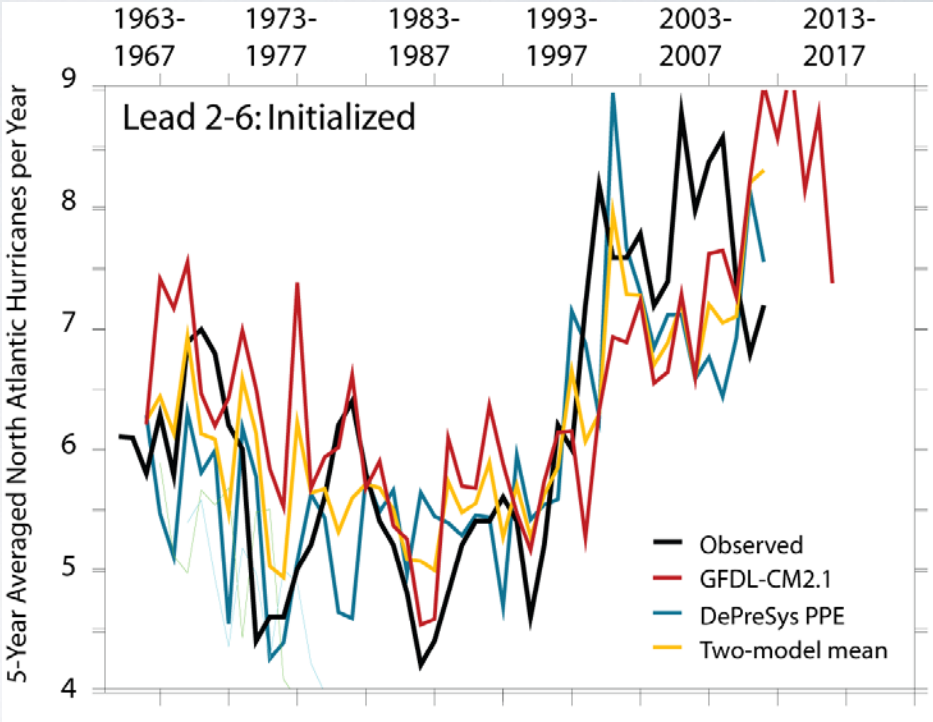
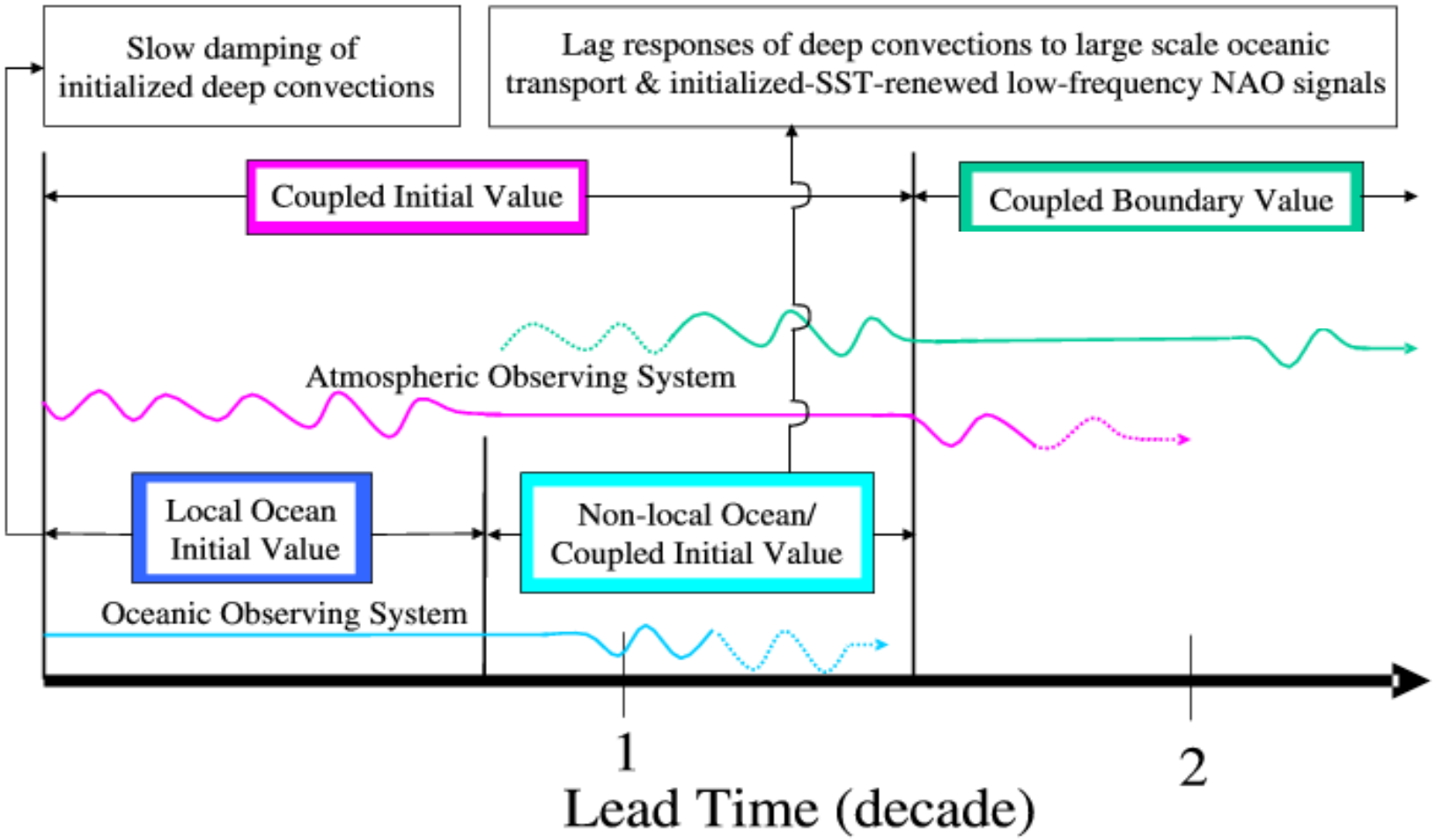


- Retrospective predictions encouraging.
- However, small sample size limits confidence
- Skill arises more from recognizing 1994-1995 shift than actually predicting it.
- This is for basinwide North Atlantic Hurricane frequency only.

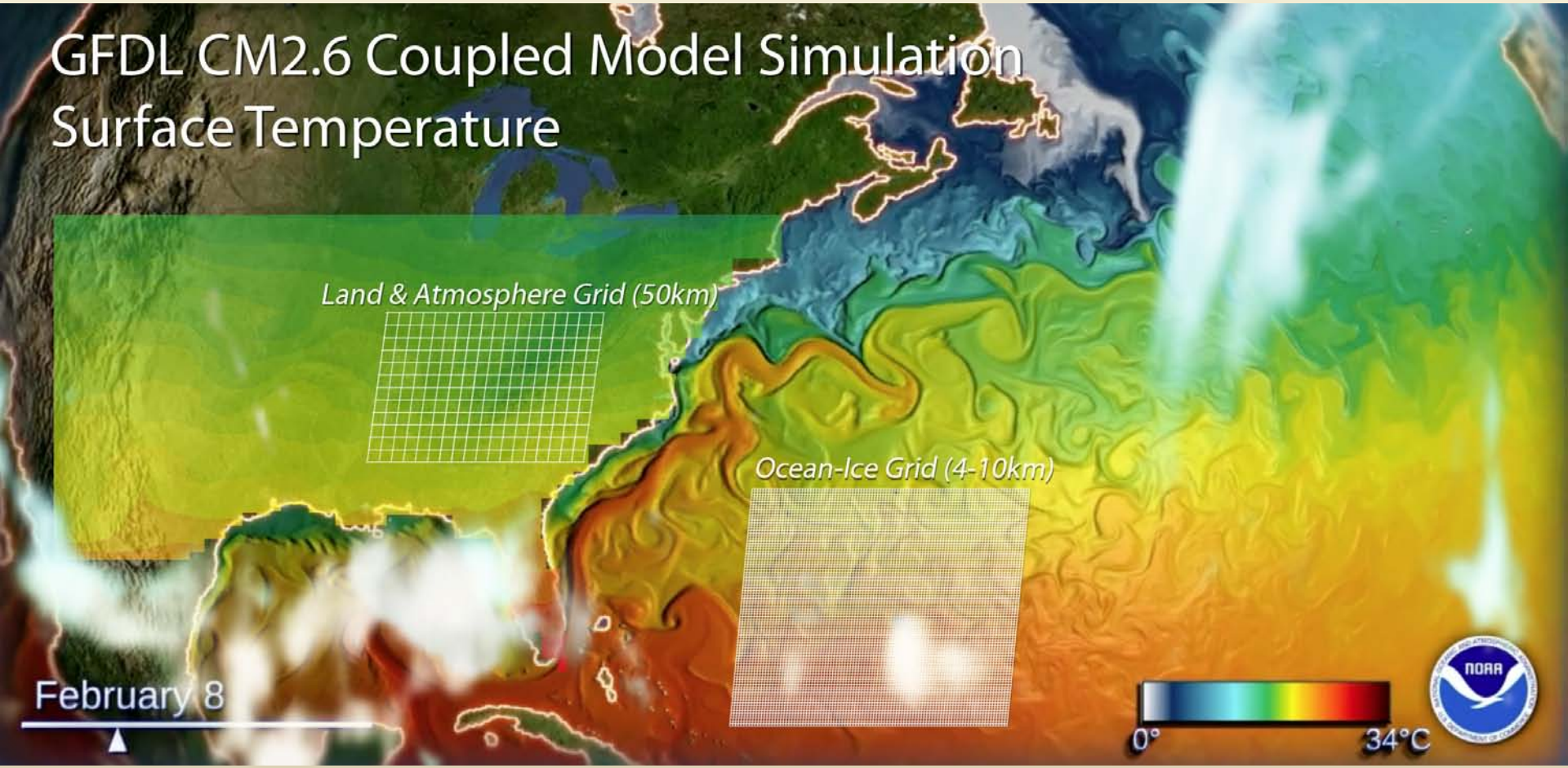
EXPERIMENTAL: NOT OFFICIAL FORECAST

Vecchi et al. (2012, J. Clim. Sub.), see also Smith et al. (2010, Science)

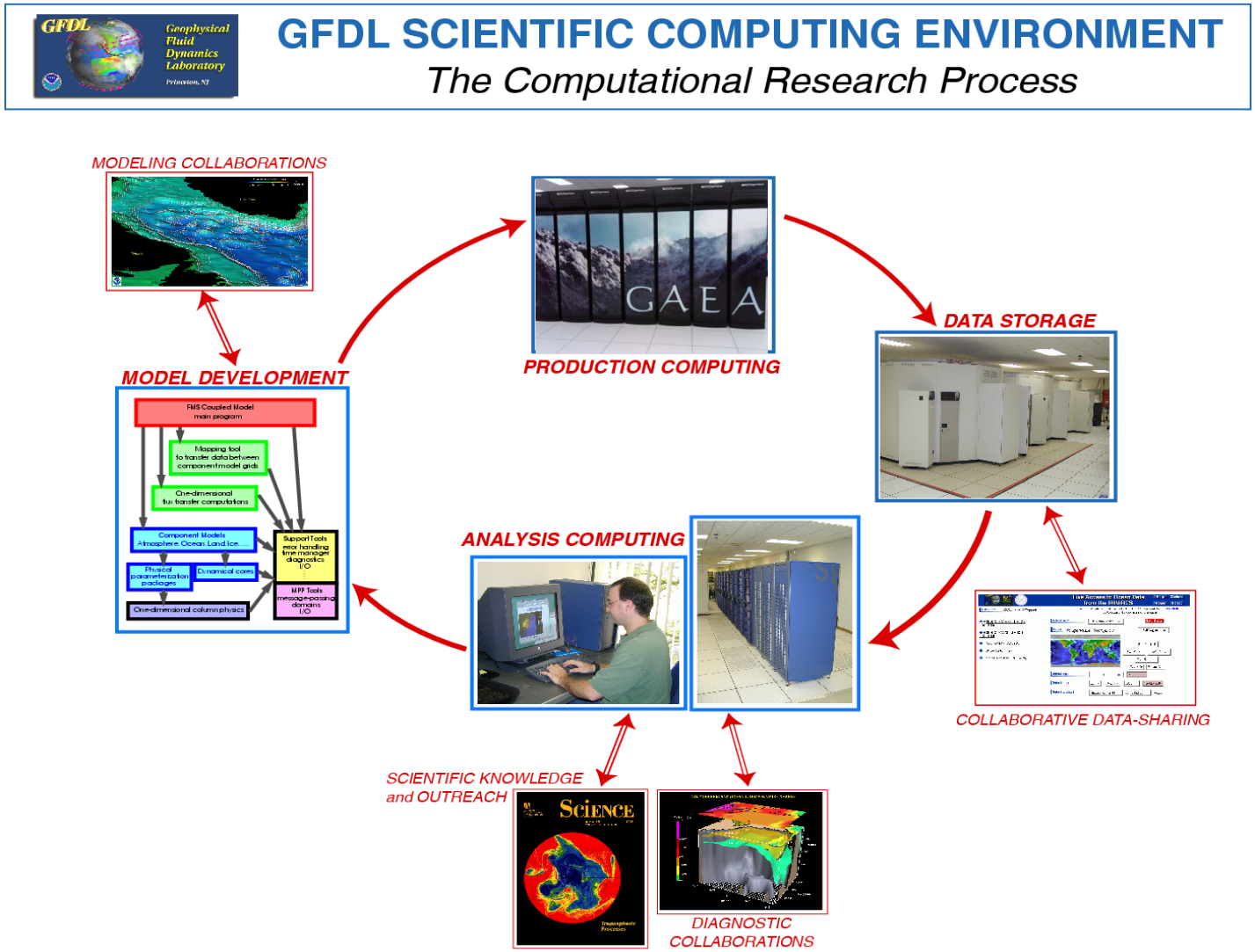
The Observing-System-Dependent Predictability of AMOC: Interannual-Multidecadal: GFDL's CDA System



Forward-looking coupled ocean atmosphere model (GFDL CM2.6)



IT components and external collaborations aligned with the Modeling and Research functions



Circa 2005

CM2.0,CM2.1 – state of the art physical climate models (1º ocn; 2º atm)

IPCC AR4 Models

Circa 2010

ESM2M,ESM2G
- Carbon cycle
- Vegetation feedback
- Ocean formulation

HIRAM
- High spatial resolution (atm only)
- Time-slice experiments
- Climate extremes

IPCC AR5 Models

CM3 (Primary Physical Model)
- Aerosols, indirect effect
- Stratosphere
- Convection, Land Model
- Atmospheric Chemistry

CM2.5
- High spatial resolution (coulpled)
- Energetic ocean
- **Variability and change in coupled system at high resolution**

CM4 ?? - drawing on what is learned from these various streams