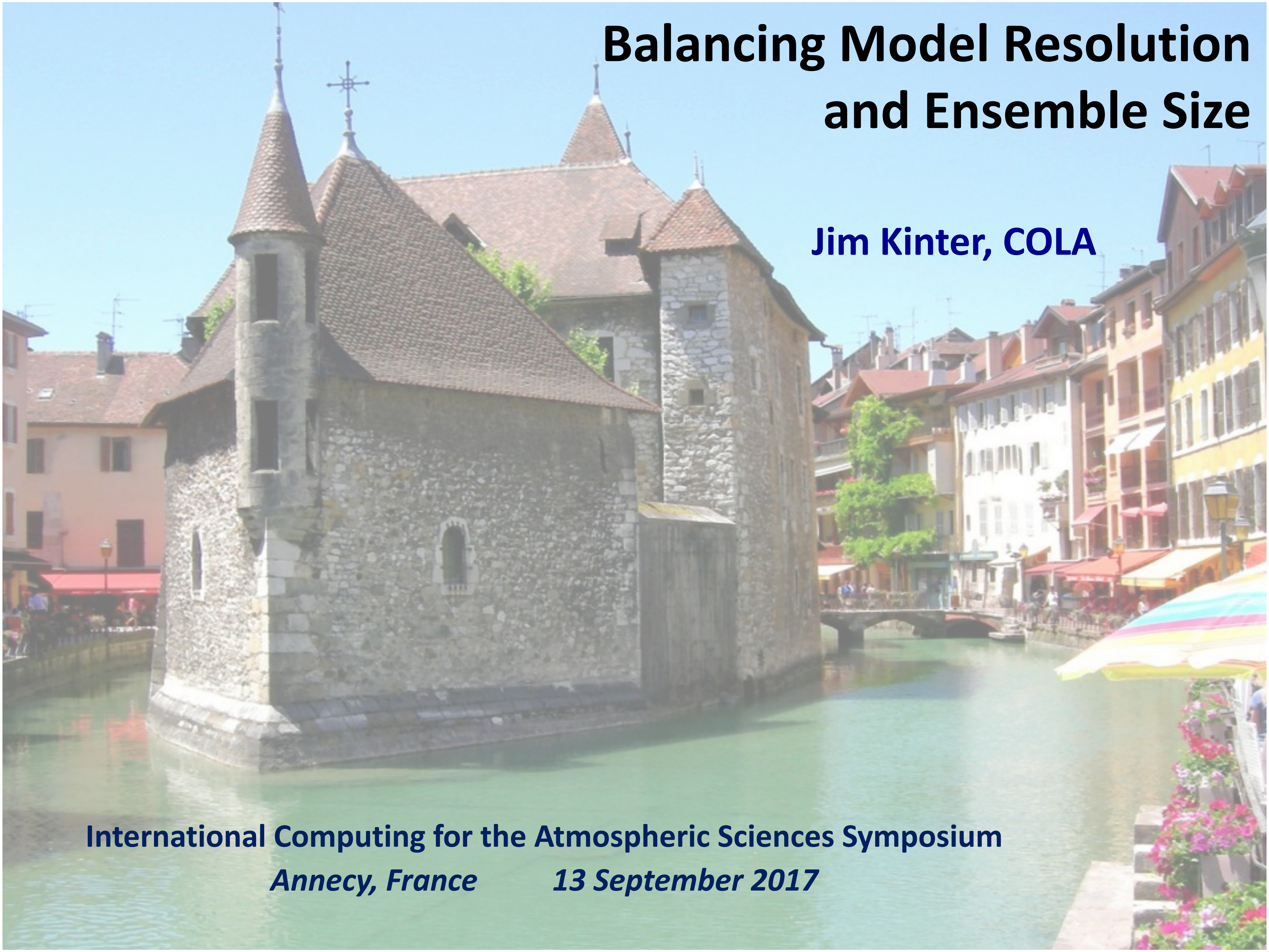


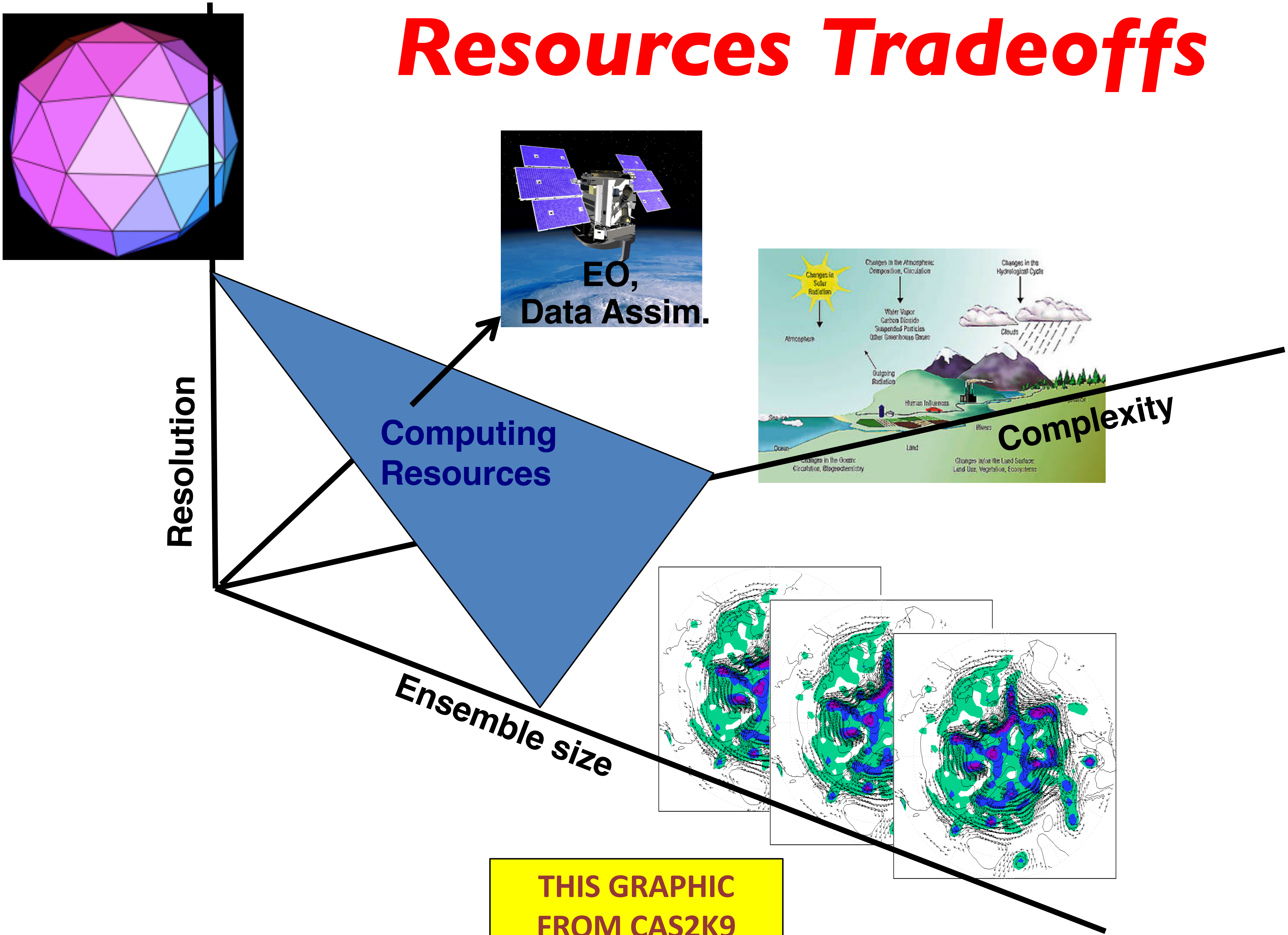
Balancing Model Resolution and Ensemble Size

Jim Kinter, COLA

International Computing for the Atmospheric Sciences Symposium

Annecy, France 13 September 2017

Resources Tradeoffs



EO,
Data Assim.

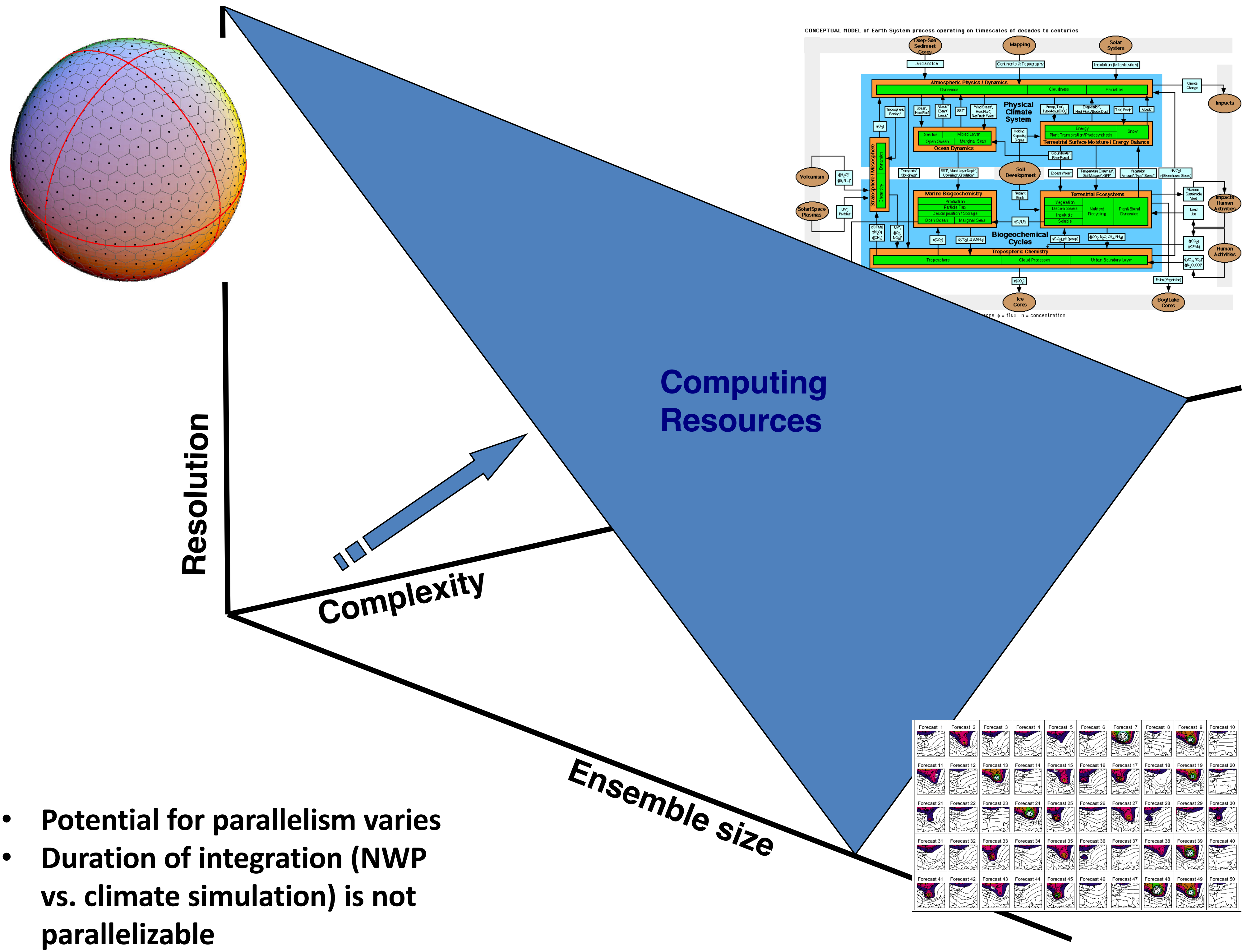
Resolution

Computing
Resources

Complexity

Ensemble size

THIS GRAPHIC
FROM CAS2K9



- Potential for parallelism varies
- Duration of integration (NWP vs. climate simulation) is not parallelizable

Much Progress in Atmospheric Modeling of Past 3.5* Decades Associated with HPC Advances

- Observing system – advances in instruments, communications and processing (system of systems)
- Data assimilation – advances in theory, algorithms, HPC
- Representation of physics
  - Including more processes – requires more HPC
  - Using obs to develop better parameterizations
- **Higher resolution** enabled by HPC (Moore's Law, S/W engineering, etc.)

* About half the time since modern era of numerical simulation of atmosphere (1947) and when I started coding and running climate models on Cyber 205

Why Increase Spatial Resolution?

- **We expect numerical solutions of fluid dynamics to converge to the continuous solution as we refine the grid**
  - Numerical solutions of continuous PDEs improve as we reduce/eliminate approximations inherent in discretizing/filtering

- **How much refinement is "enough"?**
  - It is not practical, and likely not scientific (due to Brownian motion), to attempt to **track every molecule or even every *kmol*** (~10^{26} molecules), of substance in the Earth system
  - On the other hand, a model that **tracks only features at 10^2-10^3 km-scale** is clearly inadequate
  - Where in that range of 6 orders of magnitude do we need to be?

- **What are the "breakpoints" or thresholds in resolution** between these extremes, and are there indications that we make gains by reaching those breakpoints?

Possible Breakpoints

- Baroclinic eddies in the atmosphere
  - O(1000) km scale → 150-km grid spacing*
- Ocean eddies
  - O(1º) scale → 0.1º grid
- Mesoscale eddies & tropical cyclones
  - O(100) km scale → 15 km grid spacing
  - O(10) km for internal structure → 1.5 km grid
- Tornadoes & convective cells
  - O(1) km scale → 150 m grid spacing

* Assume 6-10 grid points to resolve feature or wave

High-Resolution, High-Volume Projects at COLA

in collaboration with ECMWF, JAMSTEC, U. Tokyo, Oxford…

- **Project Athena** (2009-2012; still publishing results!): global *atmosphere-only* simulations with resolutions: 120-km ←→ 7-km
  - **Dedicated XT4 at NICS; 72 million core hours … Presented at iCAS2013**
- **Project Minerva** (2012-2014): global *coupled* seasonal predictions with different atmosphere and land surface spatial resolutions: **51 member ensembles**, 64-km ←→ 16-km, 1 degree ocean
  - **Dedicated ASD on NCAR Yellowstone; 41 million core hours**
- **Project Metis** (2016-present): global *coupled* seasonal predictions with different A, O and L spatial resolutions: 58-km ←→ 9-km, 1 degree ←→ 0.25 degree ocean
  - **Dedicated ASD on NCAR Cheyenne; 81 million core hours**

The Goddess Trilogy – Paul Dirmeyer

It Takes a Village …

- Two common themes of the Athena, Minerva and Metis projects
  - Use of several generations of the ECMWF model
  - The contributions of many people for model runs, data management and analysis
- COLA contributors
  - Ben Cash (lead), Jennifer Adams, Eric Altshuler, P. Dirmeyer, B. Doty, V. Krishnamurthy, Julia Manganello, David Straus
- ECMWF contributors
  - Roberto Buizza, Franco Molteni, Damien Decremer, Sami Saarinen
  - From earlier projects: Martin Miller, Tim Palmer, Peter Towers, Nils Wedi

Minerva Overview

System	Atmosphere model cycle	Atmosphere spectral truncation	Atmosphere vertical levels	Ocean model	Ocean horizontal res, equatorial refinement	Ocean vertical levels
MINERVA	IFS cy 38r1	T319 (64km) T639 (32 km) T1279 (16 km)	91 levels, top = 1 Pa	NEMO v 3.0/3.1	1 degree, ~ 0.3 deg. Lat	42 levels

Resolution	Start Dates	Ensembles	Length	Period of Integration
T319	May 1, Nov 1	51	7 months	1980-2013
	Nov 1	15	24 months	1980-2013
T639	May 1, Nov 1	15	7 months	1980-2013
	May 1, Nov 1	36	5 (4) months	1980-2013
	Nov 1	15	24 months	1980-2013
T1279	May 1, Nov 1	15	7 months	1980-2013

Project Metis

System	Atmosphere model cycle	Atmosphere spectral truncation	Atmosphere vertical levels	Ocean model	Ocean horizontal res.	Ocean vertical levels
METIS	IFS cy 43r1	Tco199 (64km) Tco639 (16km) Tco1279 (9km)	91 levels, top = 1 Pa	NEMO v 3.4.1	Tco199: 1º Tco639: 0.25º Tco1279: 0.25º	Tco199:42 Tco639: 75 Tco1279: 75

Resolution	Start Dates (1st of month)	Ensembles	Length	Period of Integration
$T_{CO}319$	May, Nov	25	6 months	1986-2015
	Jun, Jul, Aug, Dec, Jan, Feb	15	2 months	1986-2015
$T_{CO}639$	May, Nov	25	6 months	1986-2015
	Jun, Jul, Aug, Dec, Jan, Feb	15	2 months	1986-2015
$T_{CO}1279$	Nov	15	2 months	1986-2015

~ 80 million Cheyenne hours, 850 TB analyzable output

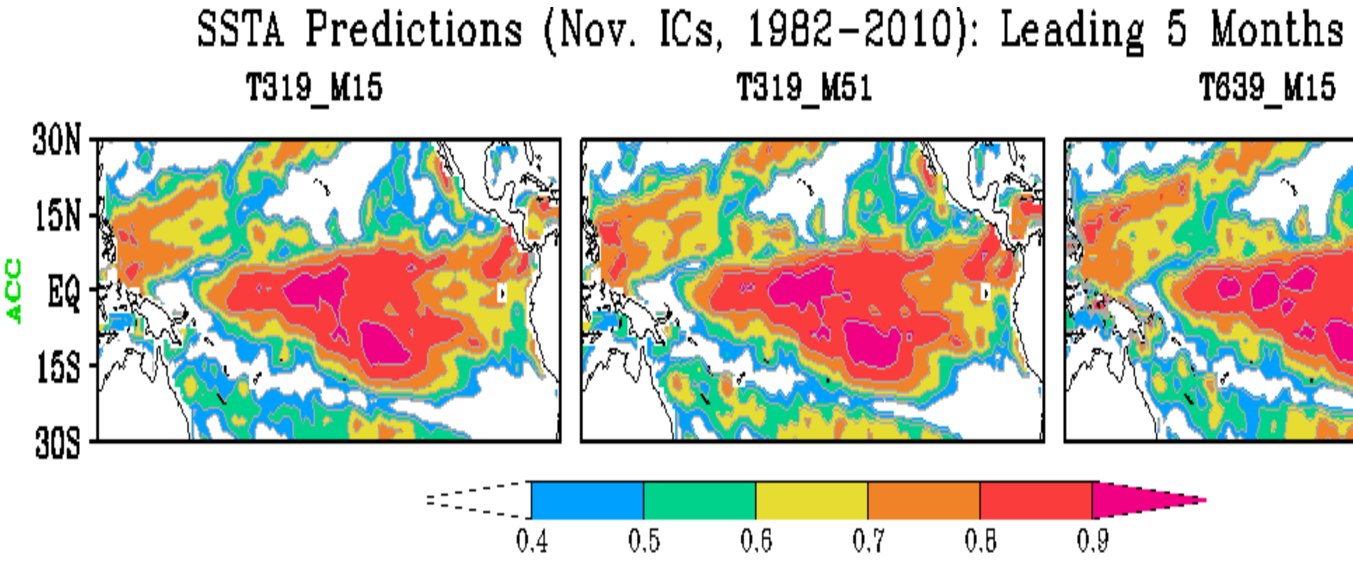
Selected Research Highlights from High Resolution Climate Models

- **Unexpected Challenges**:
  - ENSO
  - Indian Summer Monsoon

- **Interesting Successes**:
  - Tropical Cyclones
  - California Drought

ENSO Forecast Skill in Minerva

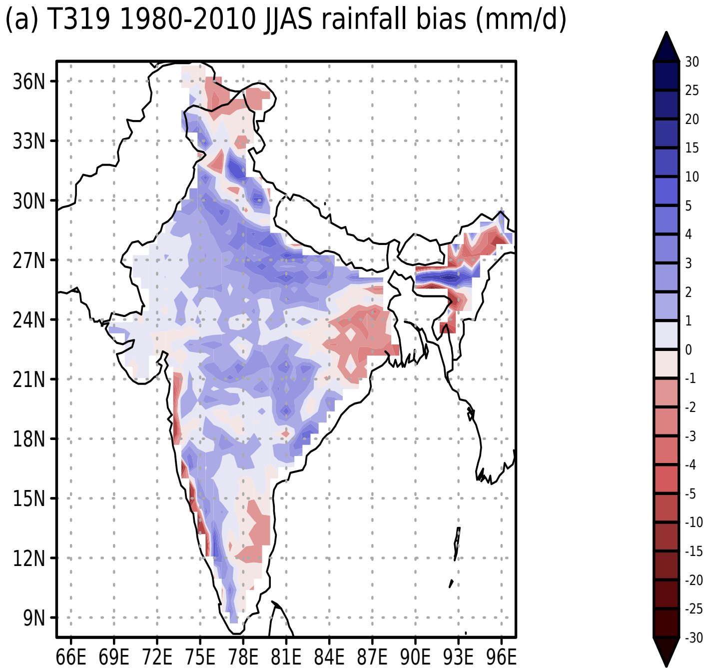
(simultaneous correlation predicting March SSTA from 1 Nov ICs ensemble mean)



Almost no sensitivity to resolution or ensemble size

Mean Monsoon (JJAS) Rainfall Bias in Minerva

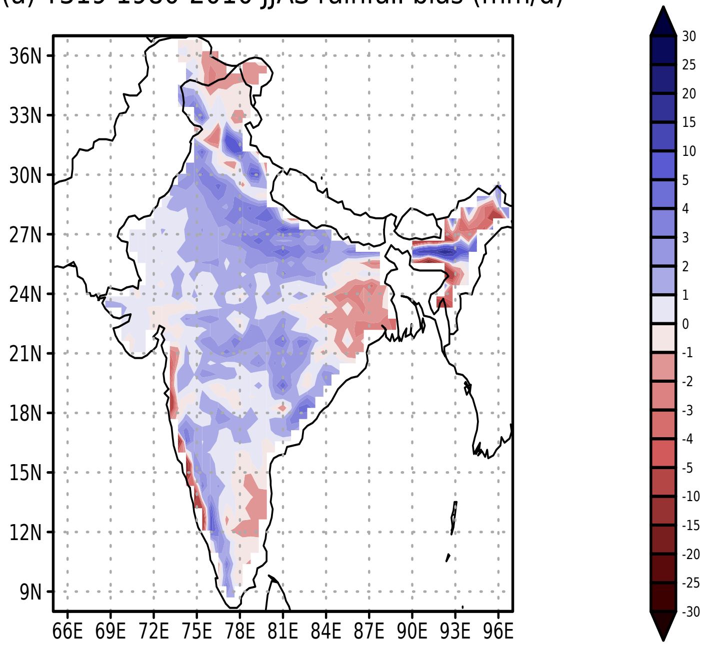
T319



Mean Monsoon (JJAS) Rainfall Bias in Minerva

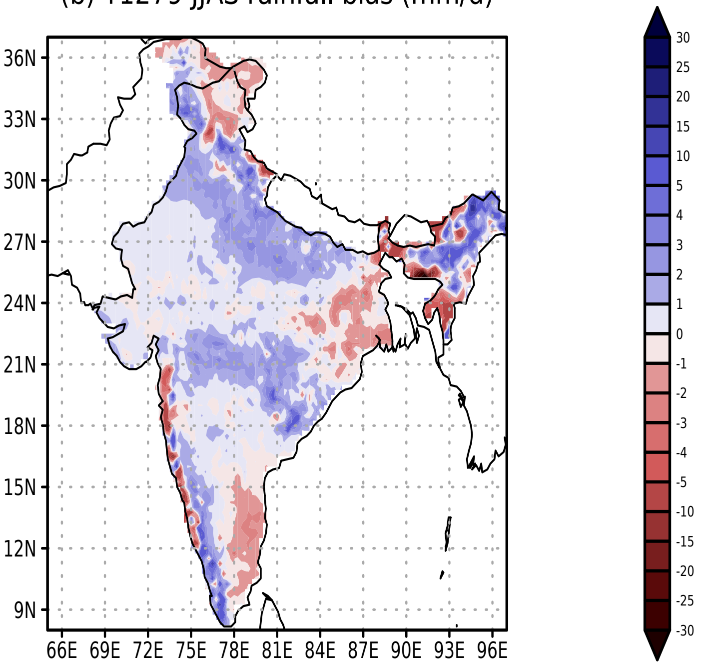
T319

(a) T319 1980-2010 JJAS rainfall bias (mm/d)



T1279

(b) T1279 JJAS rainfall bias (mm/d)

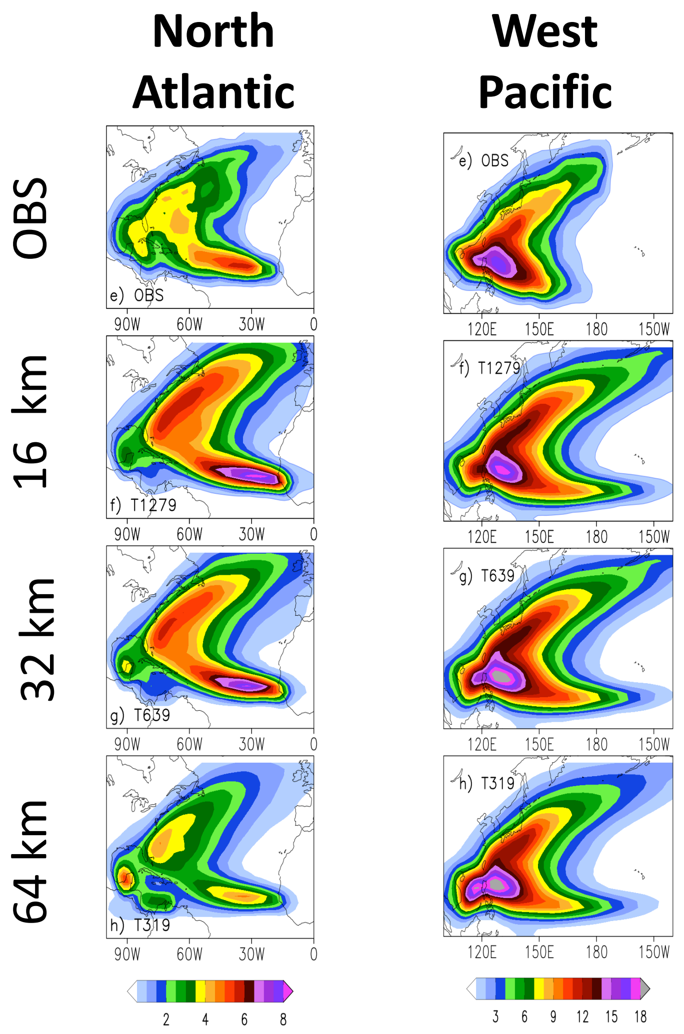


Almost no sensitivity to resolution

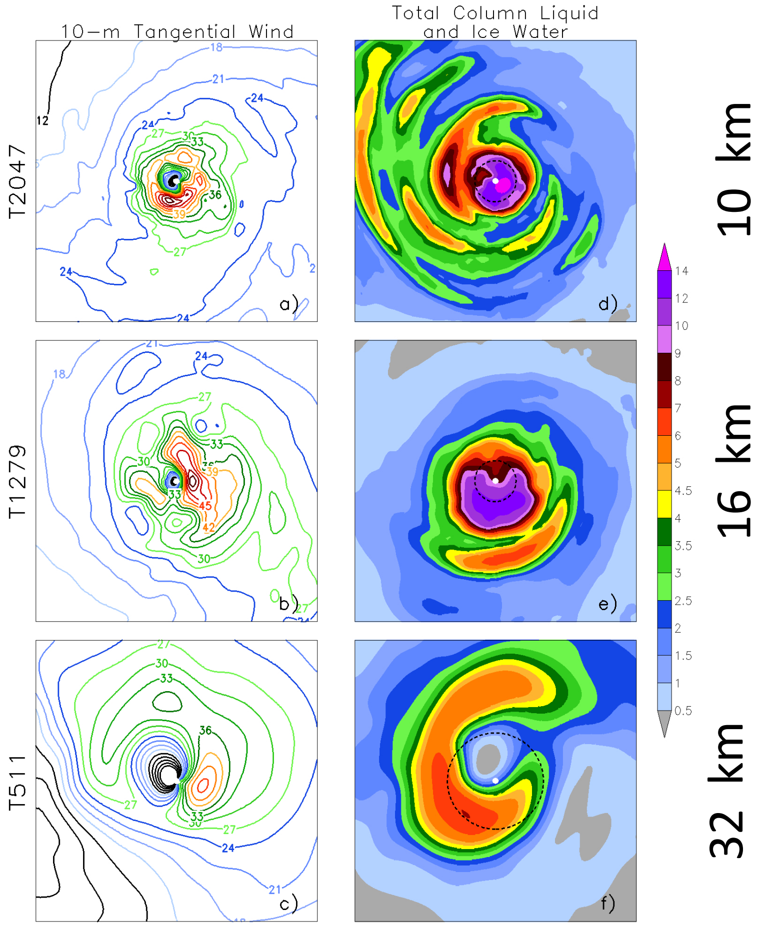
Tropical Cyclones

I. Sensitivity of *Simulated* Tropical Cyclone Structure to Atmospheric Horizontal Resolution

Sensitivity to Resolution: Tropical Cyclones



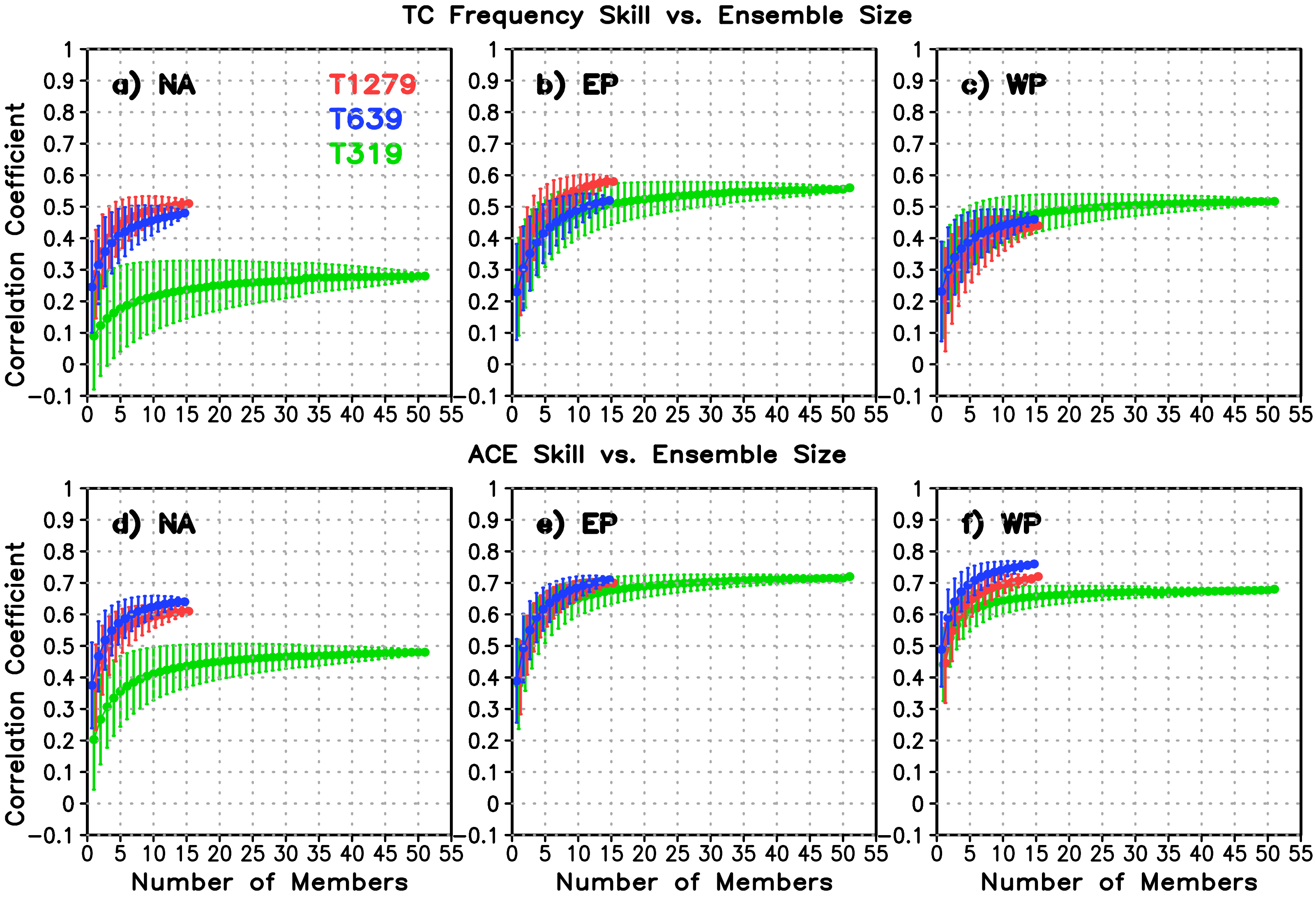
Tropical cyclone structure & statistics improve dramatically with resolution



Courtesy Julia Manganello

II. Sensitivity of *Hindcast* Skill to Atmospheric Horizontal Resolution and Ensemble Size

Seasonal Statistics of Tropical Cyclones in Minerva

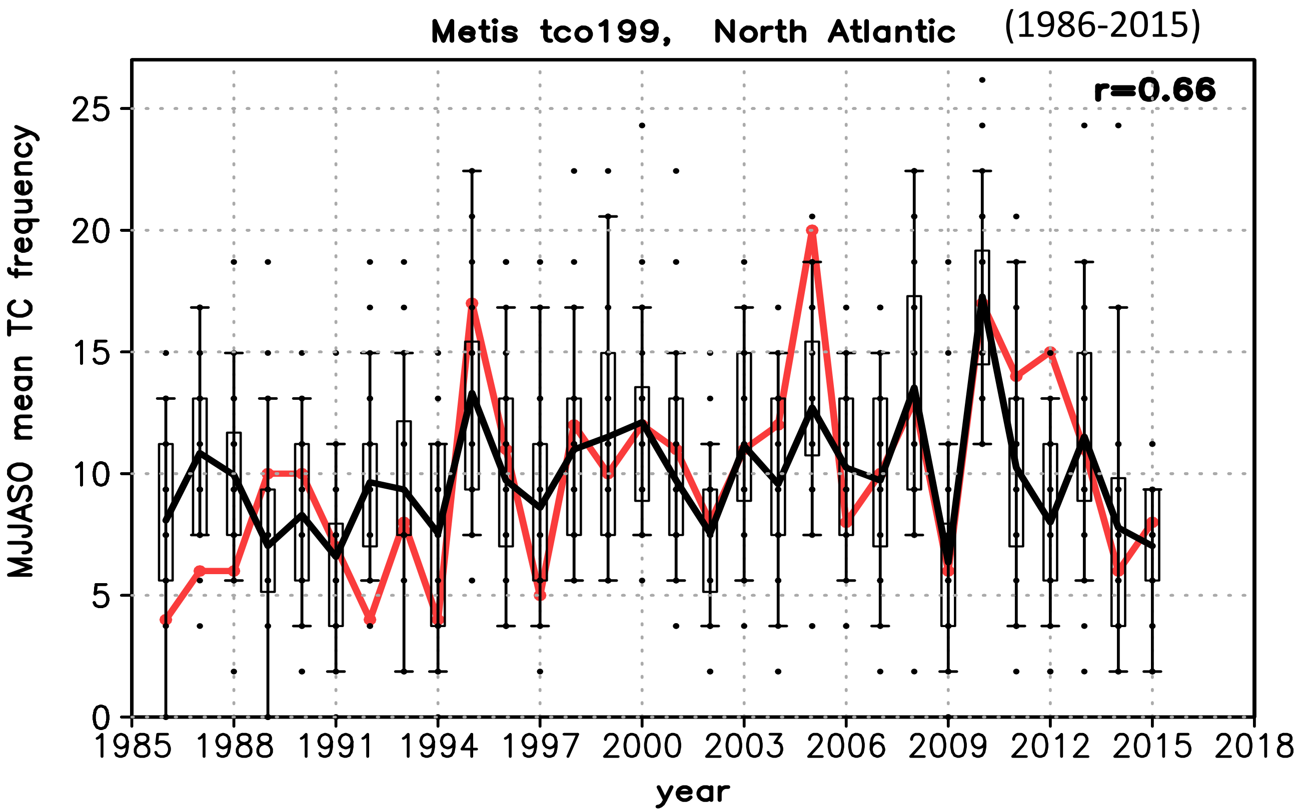

TC Frequency Skill vs. Ensemble Size

ACE Skill vs. Ensemble Size

Courtesy Julia Manganello

III. *Metis* skill at Base Resolution (T$_{co}$199: 50-km atmosphere, 1º ocean) Higher than *Minerva* at Any Resolution

Correlation Skill of North Atlantic TC frequency and ACE in Minerva and Metis Tco199

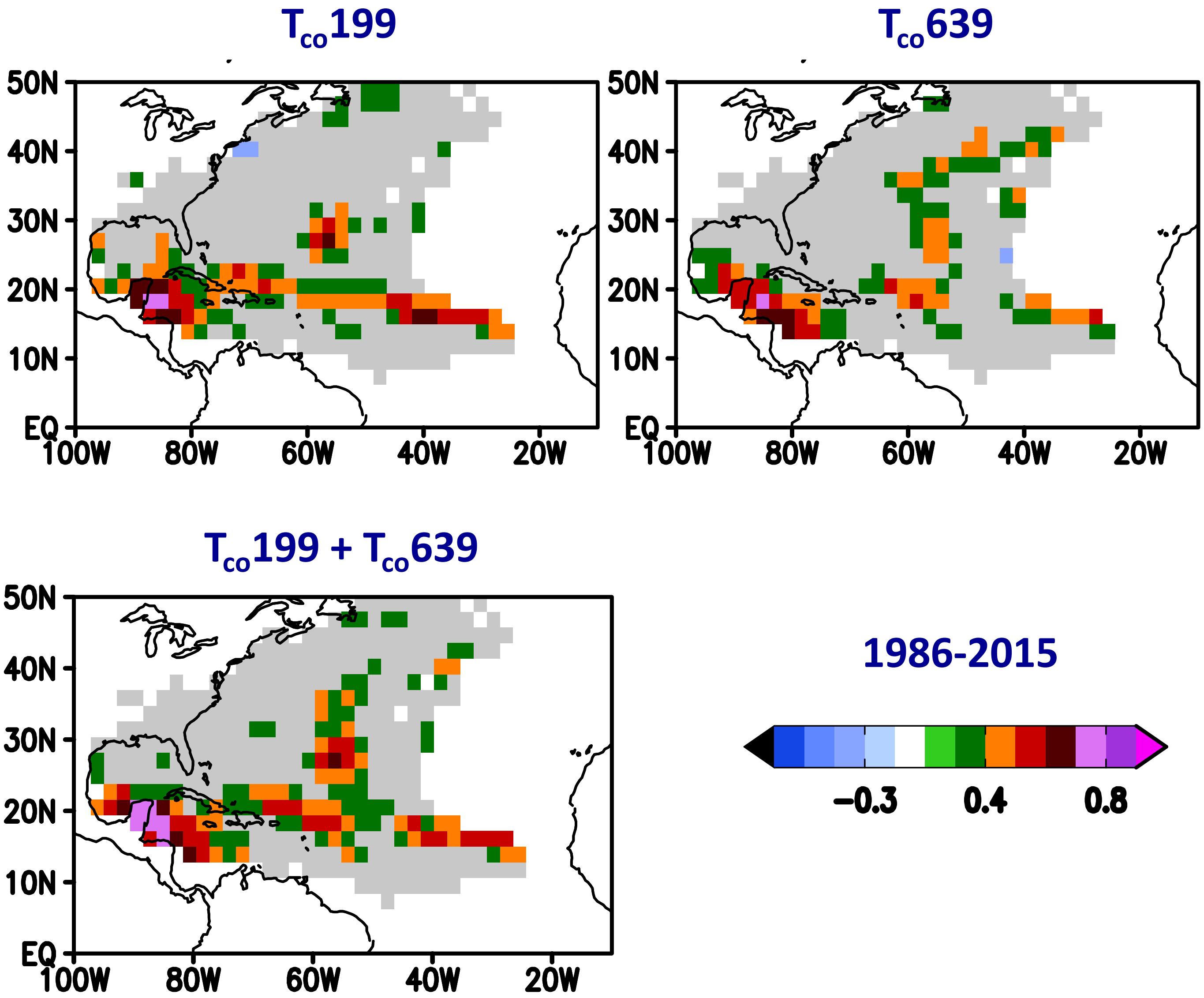


Model/Basin	NA	ENP	WNP
TC Frequency (1986-2011)			
Metis Tco199	**0.72**	**0.62**	**0.64**
Minerva T1279	**0.69**	**0.52**	**0.60**
Minerva T639	**0.68**	**0.50**	**0.44**
Minerva T319	0.27	**0.55**	**0.55**
TC Frequency (1990-2015)			
Metis Tco199	**0.71**	**0.71**	**0.58**
ACE (1990-2015)			
Metis Tco199	**0.60**	**0.75**	**0.81**

Boldface indicates stat. significance at the 95% confidence level

Courtesy Julia Manganello

Rank Correlation Skill of Regional TC Activity in Metis T_{co}199 and T_{co}639



T_{co}199

T_{co}639

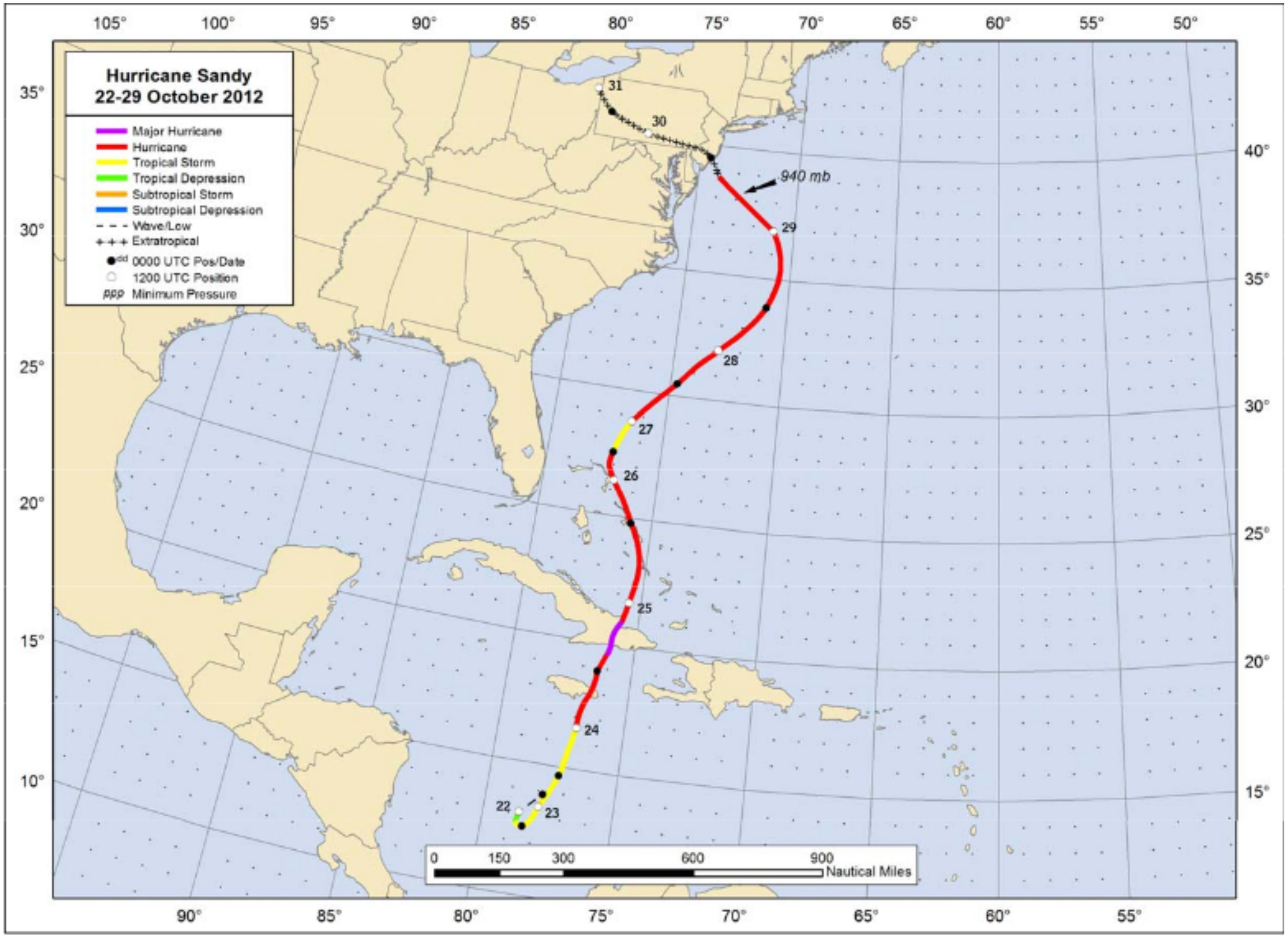
T_{co}199 + T_{co}639

1986-2015

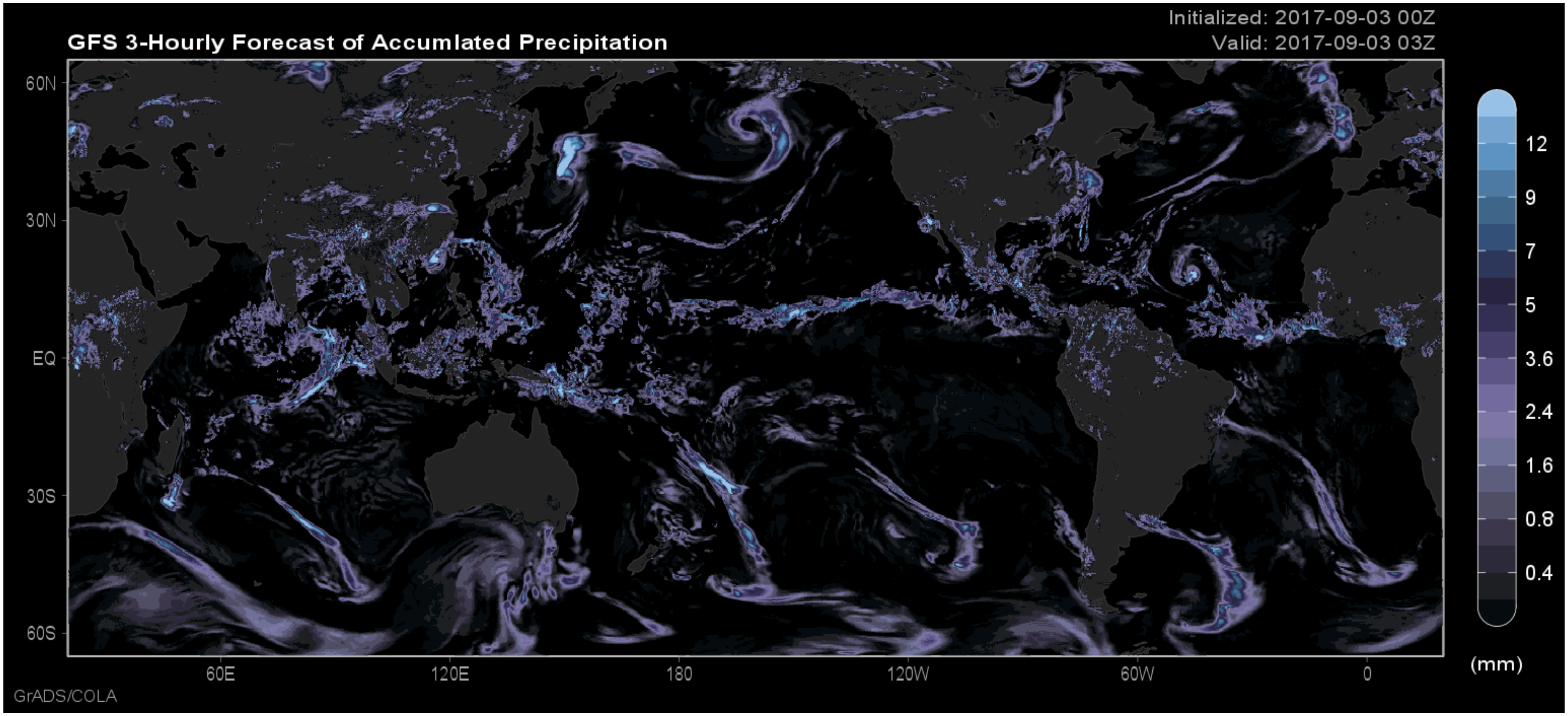
Courtesy Julia Manganello

IV. Ensemble Forecasts With High-Atmospheric Resolution Coupled Prediction Systems: "Extensions" of Observational Record to Compile Statistics of Rare and Potentially Highly Destructive Events

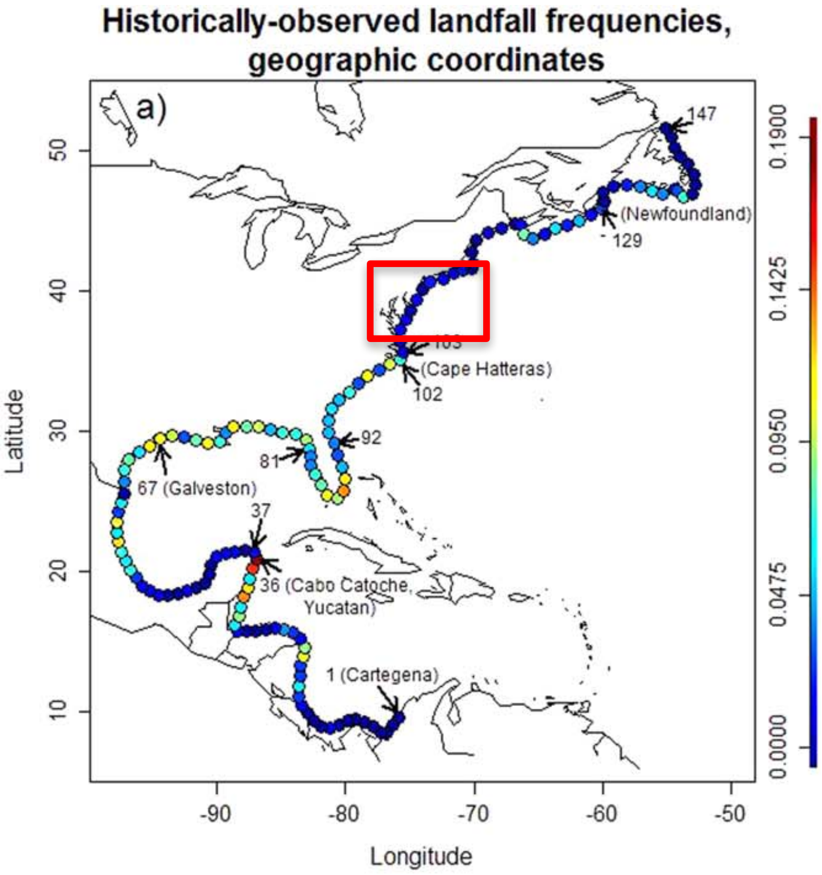
Mid-Atlantic Landfall Example: Hurricane Sandy



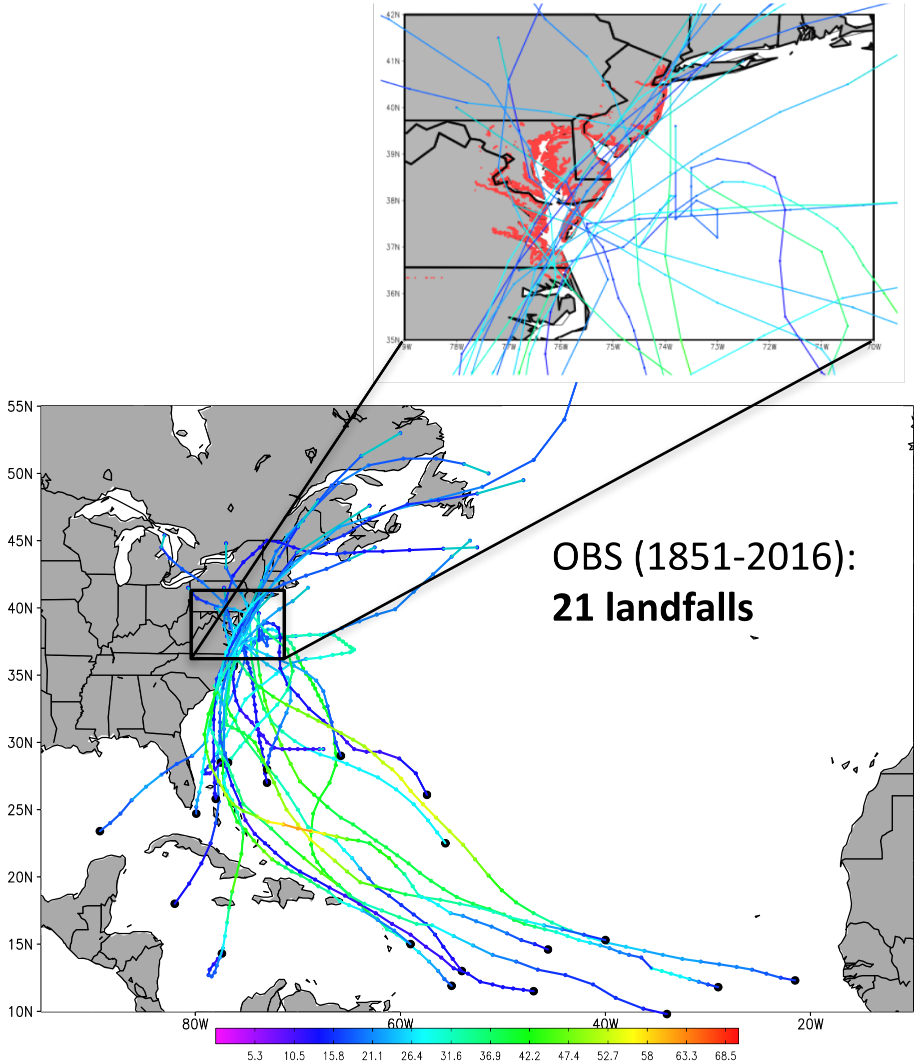
Hurricane Irma – GFS Forecast from Sunday, 3 September 2017



TC Landfalls in Mid-Atlantic – Among Least Frequent in US


Historically-observed landfall frequencies, geographic coordinates

From Tolwinski-Ward (JAMES, 2015; Fig. 1a).



OBS (1851-2016):
21 landfalls

OBS (1980-2016): 6 landfalls (TS Dean’83, MH Bertha’96, MH Floyd’99, SS #22’05, MH Irene’11, MH Sandy’12)

Mid-Atlantic TC Landfall Basic Statistics in OBS and Minerva

	IBTrACS v03r07		**T1279** (1980-2013;15 ens.) *(510 seas.)*	**T639** (1980-2013; 15 ens.) *(510 seas.)*	**T319** (1980-2012)	
	1851-2016 *(166 seas.)*	1900-2016 *(117 seas.)*			15 ens. *(495 seas.)*	51 ens. *(1,683 seas.)*
Average rate[1]	0.13	0.11	0.10	0.09	0.09	0.09
Average Return Period[2]	8	9	**10**	**11**	**11**	**11**
Probability of Landfall[3,4]	12%	11%	9%	9%	9%	9%
Probability of landfall in the next 10 seasons	74%	69%	64%	61%	63%	61%

[1] per MJJASON season

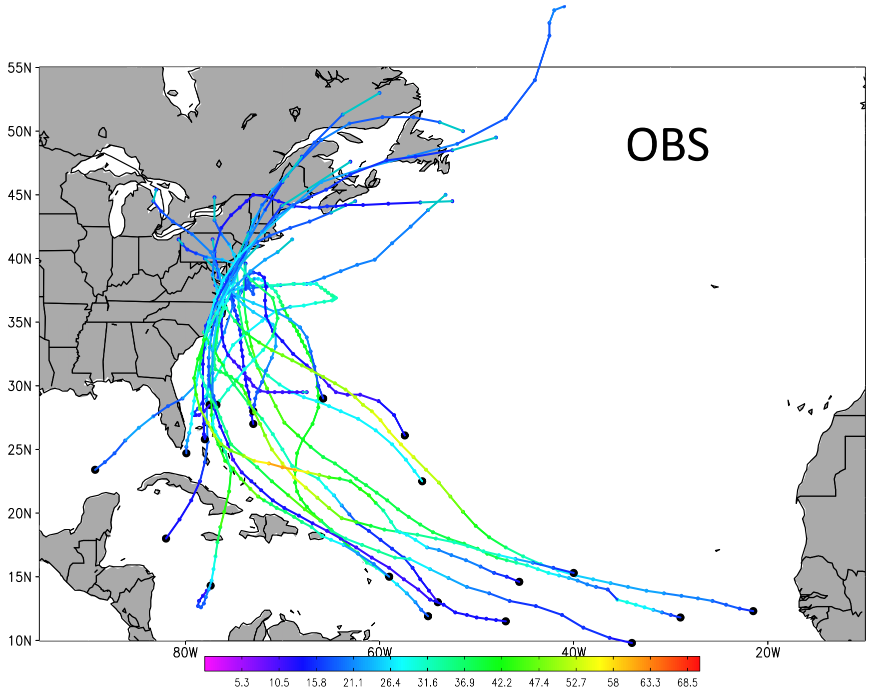
[2] in seasons (MJJASON)

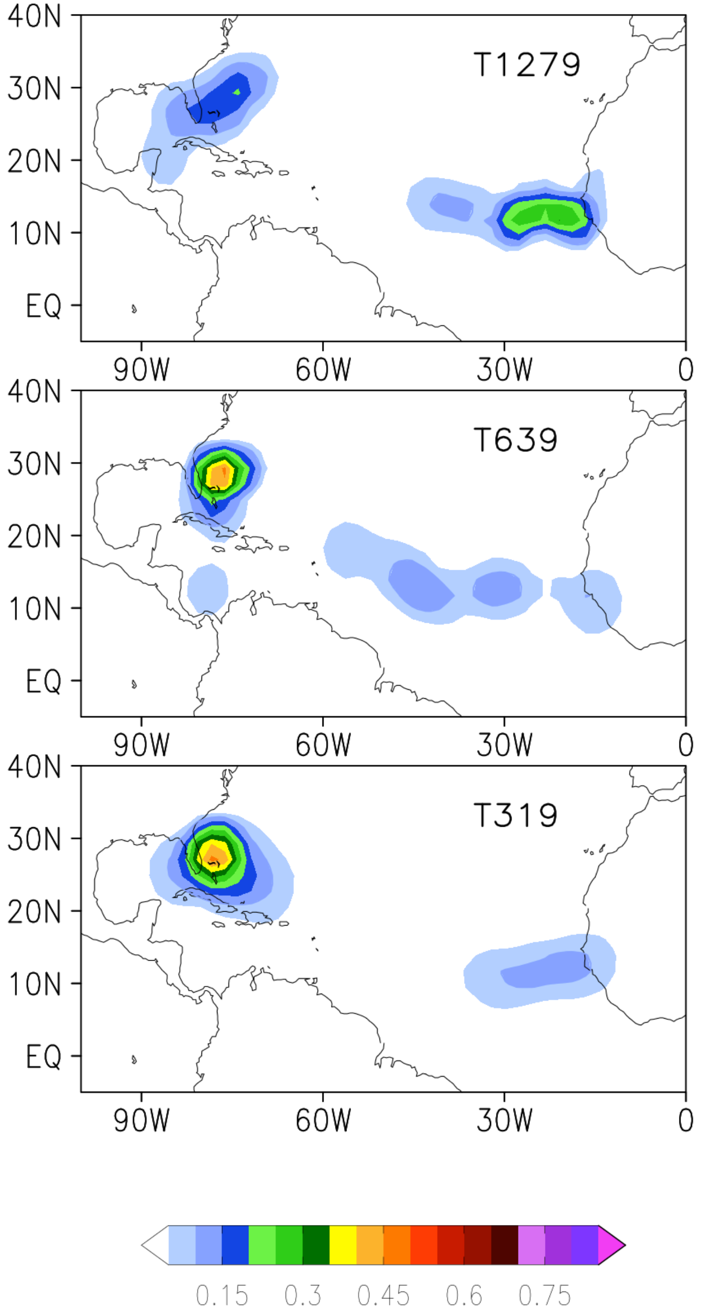
[3] in a MJJASON season

[4] Probability of a landfall of 1 or more TCs based on the Poisson distribution. Differences between the model and observational values are statistically insignificant (at 95% confidence limit).

Courtesy Julia Manganello

Formation Regions of TCs with Mid-Atlantic Landfalls

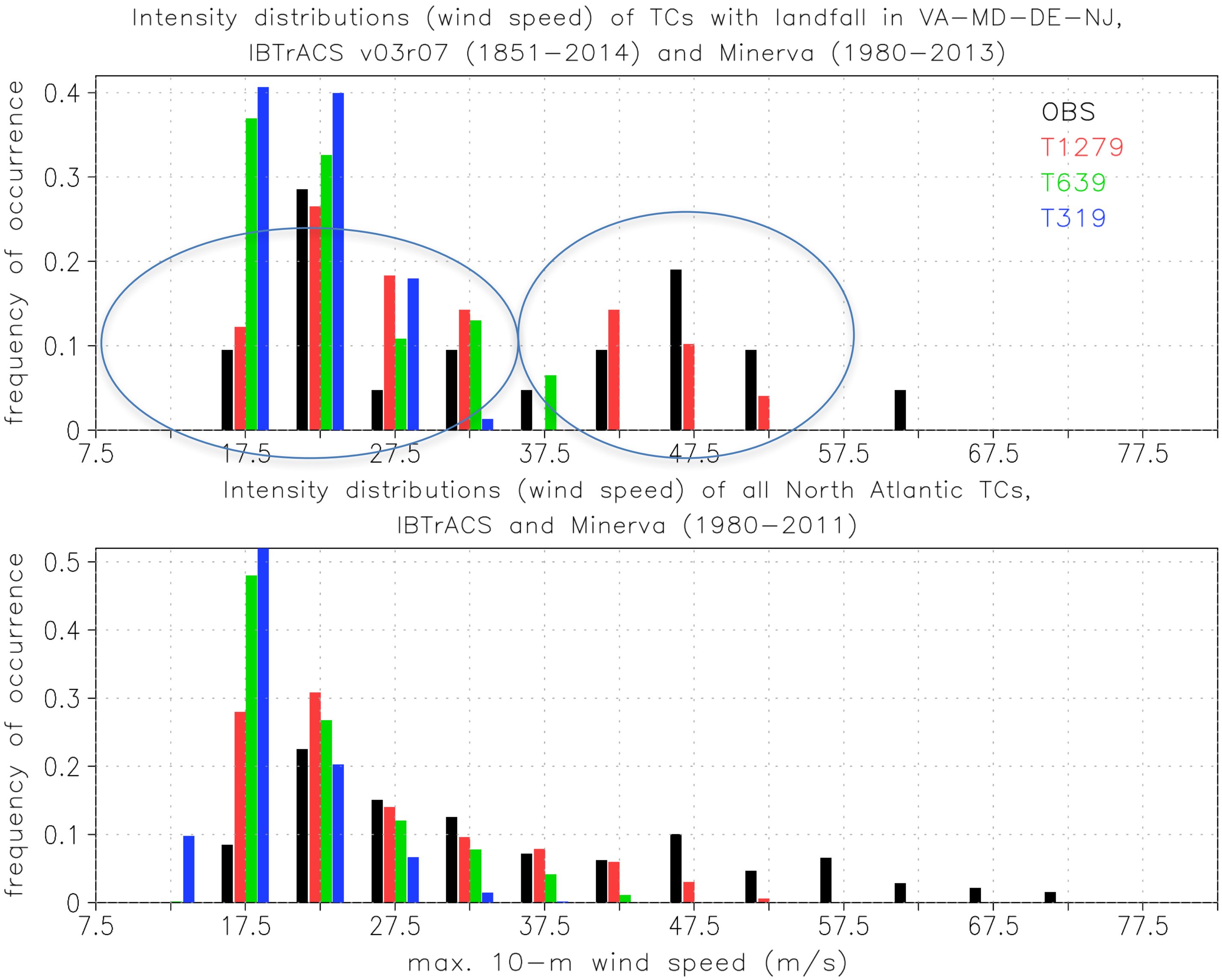




Courtesy Julia Manganello

Intensity Distribution

(10m wind speed)

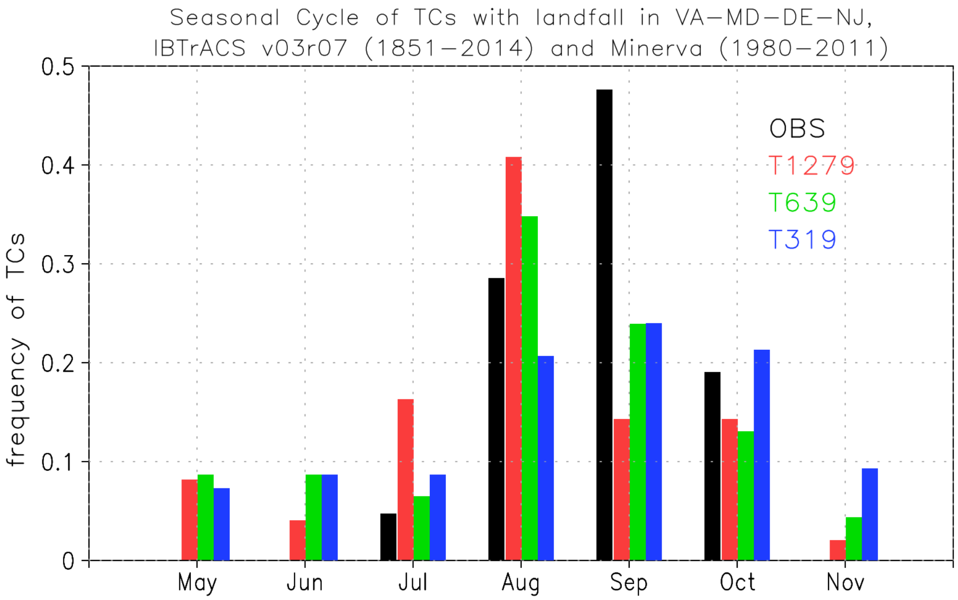


TCs with landfall in the Mid-Atlantic

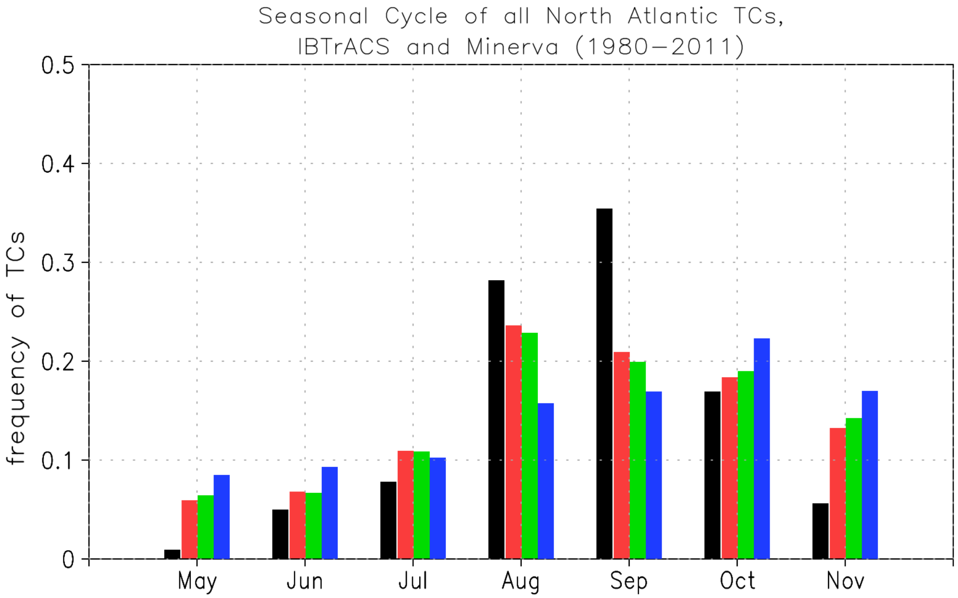
All North Atlantic TCs

Courtesy Julia Manganello

Seasonal Cycle


Seasonal Cycle of TCs with landfall in VA–MD–DE–NJ, IBTrACS v03r07 (1851–2014) and Minerva (1980–2011)

TCs with landfall in the Mid-Atlantic


Seasonal Cycle of all North Atlantic TCs, IBTrACS and Minerva (1980–2011)

All North Atlantic TCs

Courtesy Julia Manganello

California Drought

- California experienced severe drought from 2011 - 2017
  - Mostly alleviated by record precipitation in winter 2016/17

- Multiple years of below-average rainfall
  - Large deficiencies during winter rainy season

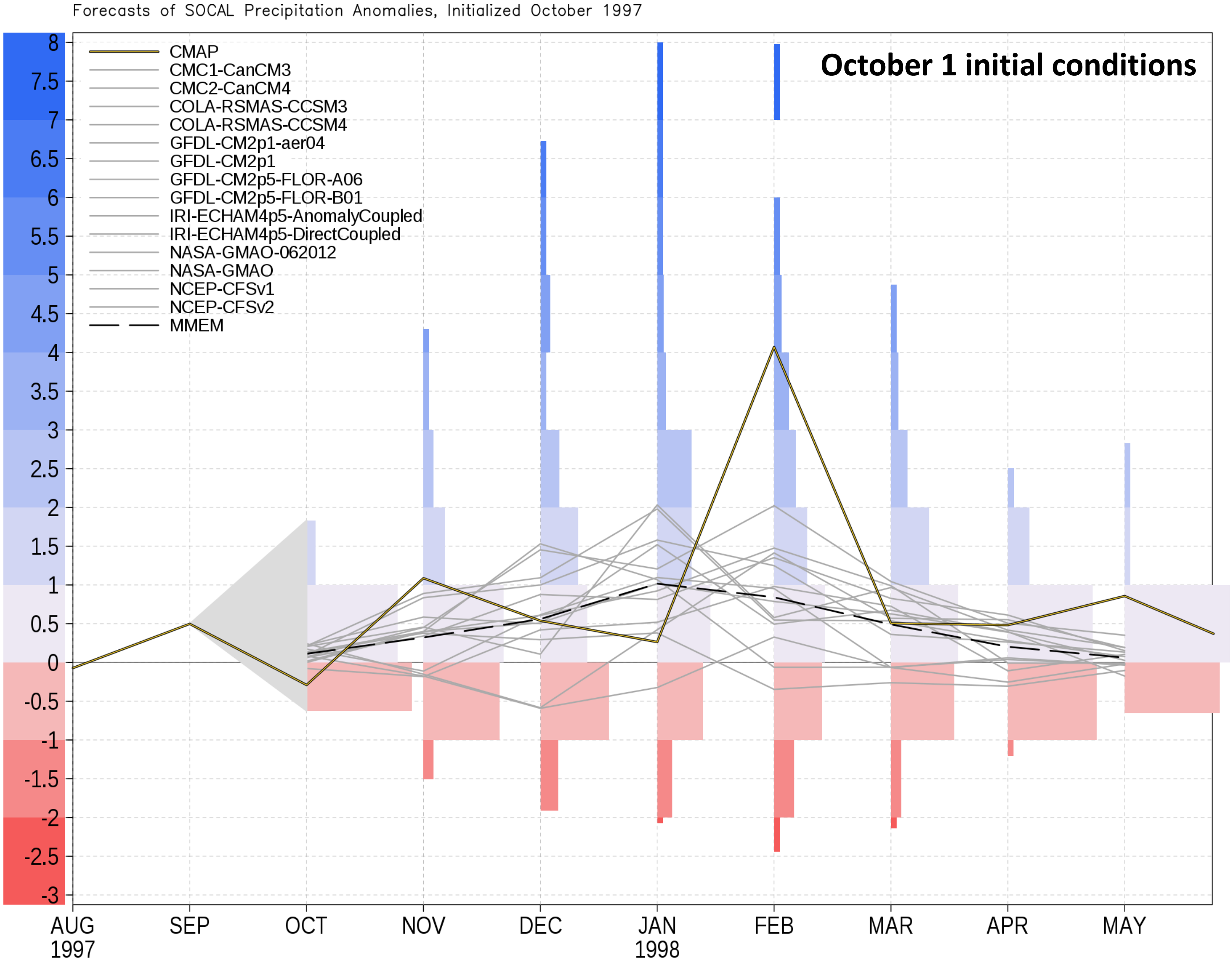
- Widespread hope/expectation that massive 2015/16 El Niño event would break the drought
  - Previous large El Niño events associated with above average winter rains
  - Seasonal forecasts suggested this would be true again
  - Slightly below normal rainfall resulted
  - **WHY DIDN'T THE DOG BARK?**

1997/98 SOCAL precipitation in the NMME

Anomalies relative to 1982-2009 hindcasts

Above average rainfall observed, particularly in February

Ensemble mean predicts above average rainfall



October 1 initial conditions

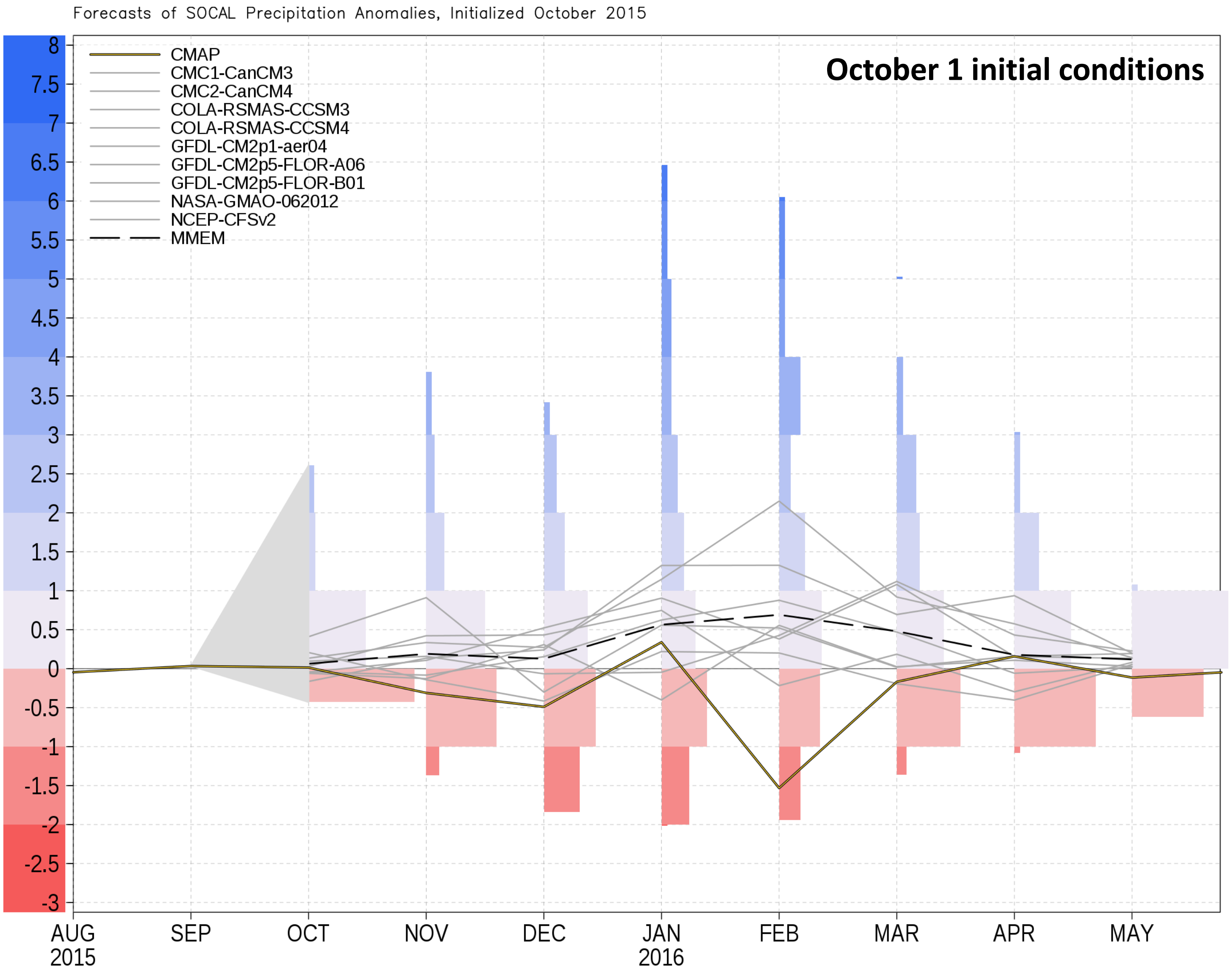
Courtesy Ben Cash

2015/16 SOCAL precipitation in the NMME

Anomalies relative to 1982-2009 hindcasts

Observed Feb. rainfall below average

Ensemble mean is still above average

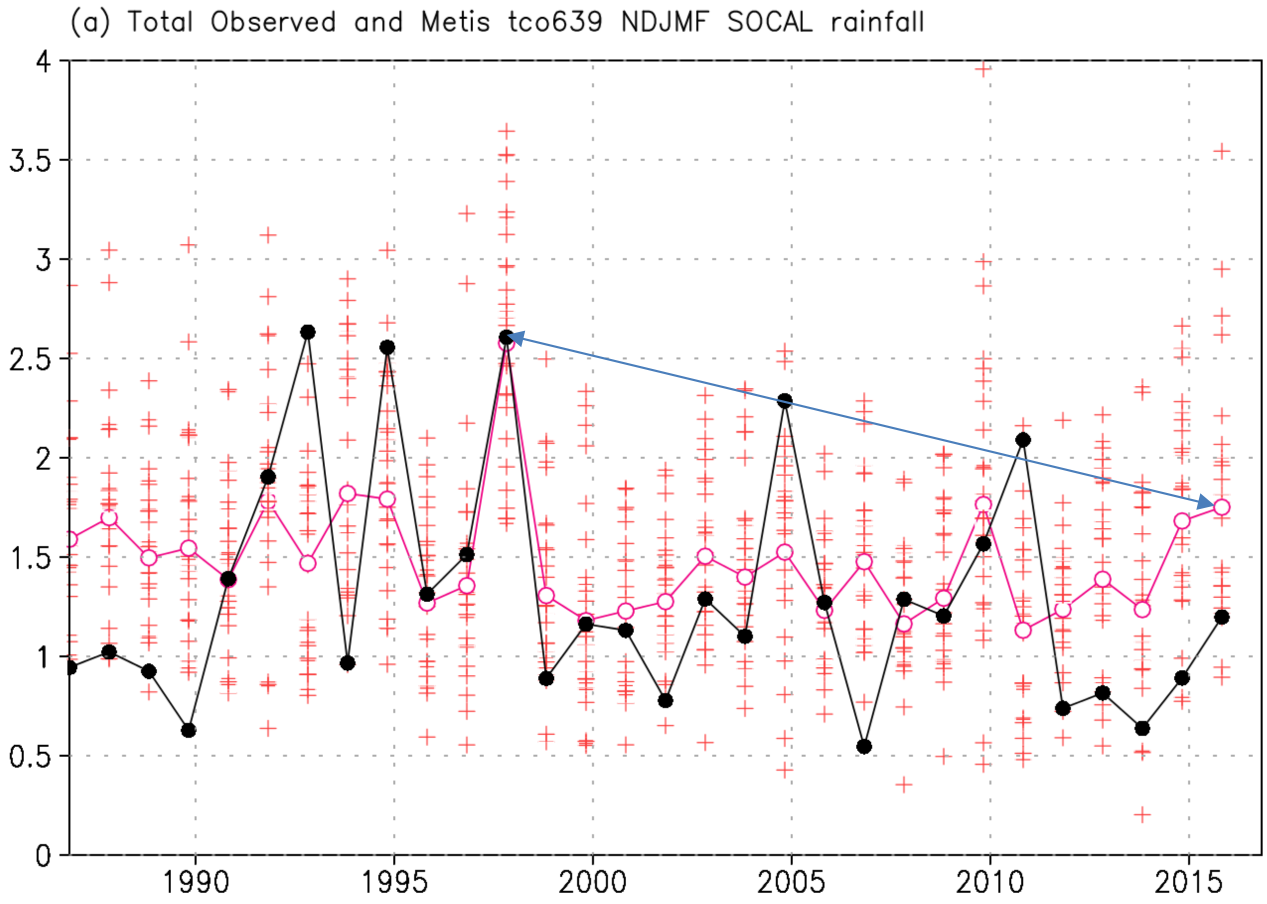


Courtesy Ben Cash

SOCAL Rainfall in Project Metis

- **Clear reduction in ensemble mean forecast from 1997/98 to 2015/16**

- Much larger ensemble spread



Benjamin Cash – NOAA Review: Year 3 - June 29, 2017

Courtesy Ben Cash

SOCAL Rainfall in Project Metis

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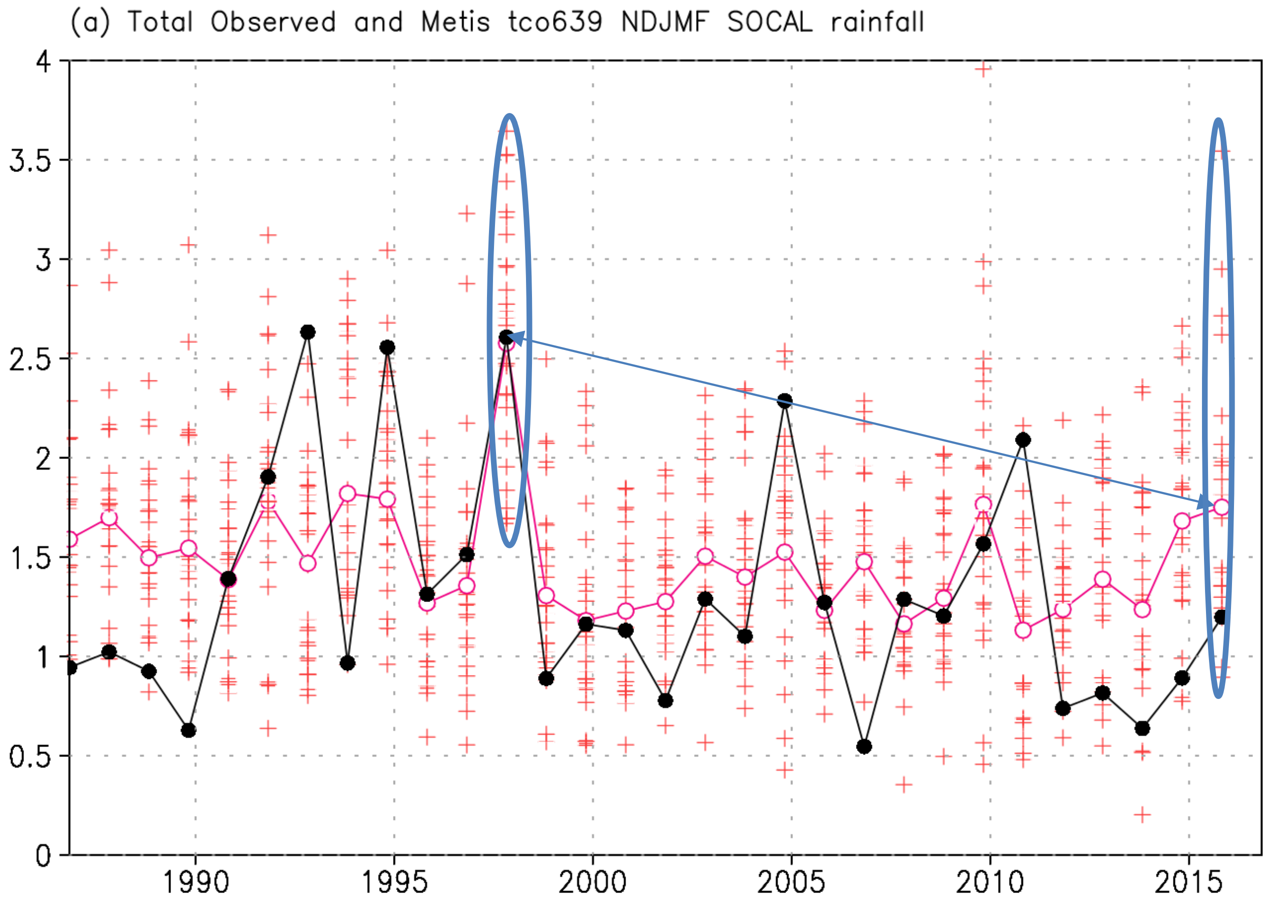
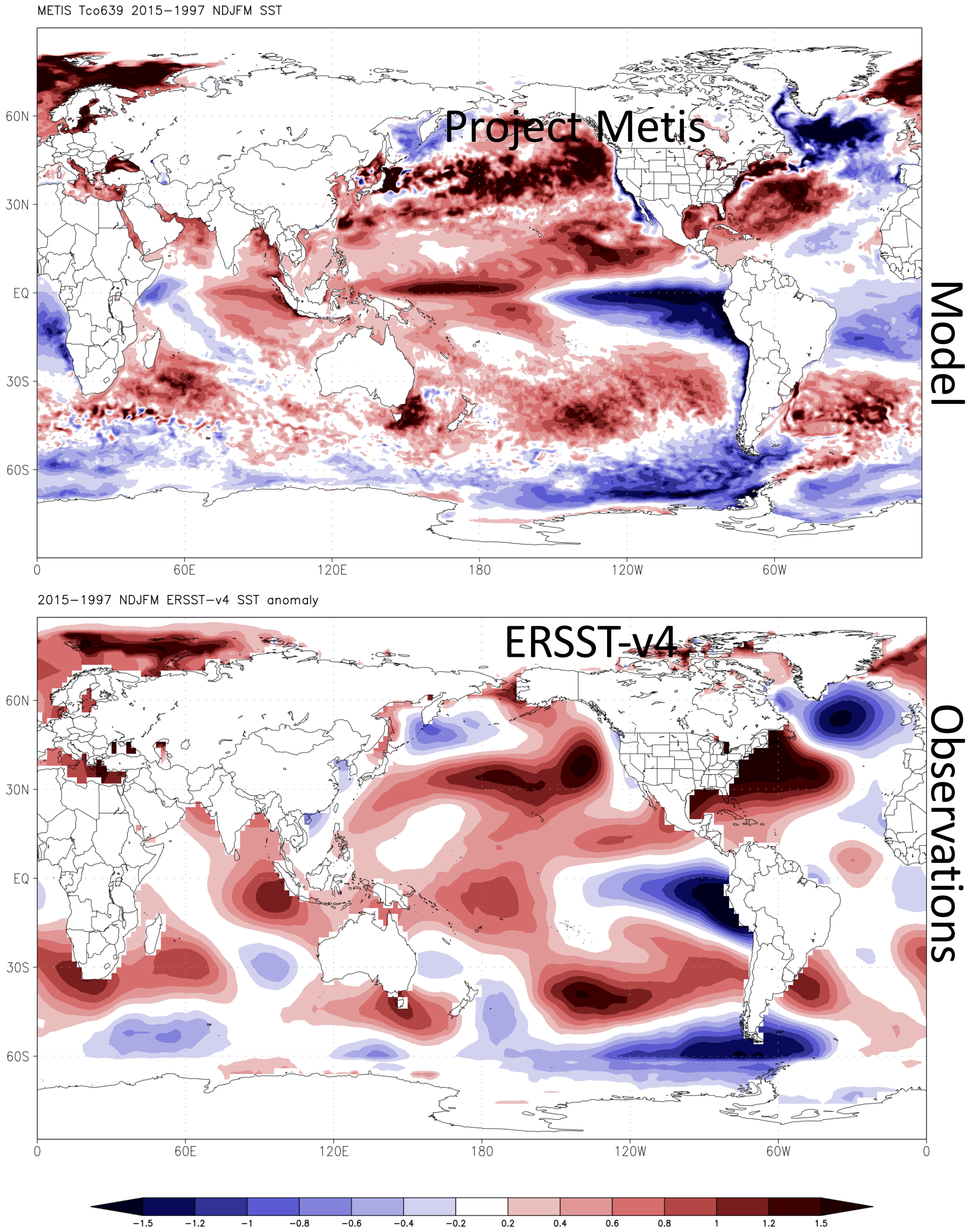


Benjamin Cash – NOAA Review: Year 3 - June 29, 2017

Courtesy Ben Cash

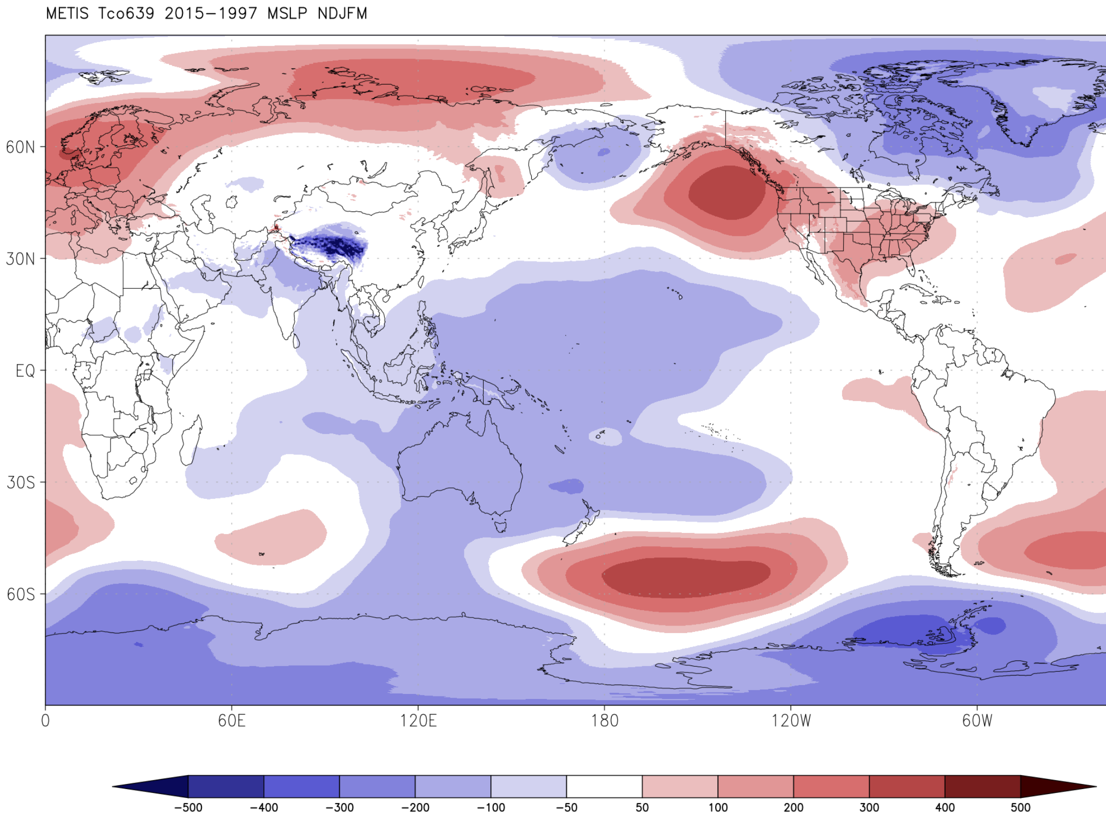
Simulated and Observed SST Differences: 2015/16 – 1997/1998

- Metis clearly captures differences in eastern tropical Pacific between the two events



Simulated MSLP Differences: 2015/16 – 1997/1998

- Large forced difference in north Pacific circulation
- Region known to affect SOCAL rainfall
- **Clear difference in forced response**
- **Large unforced component as well (not shown)**



Benjamin Cash – NOAA Review: Year 3 - June 29, 2017

Courtesy Ben Cash

Conclusions

- **ENSO and Asian Monsoon**
  - Forecast skill relatively insensitive to resolution in Minerva
  - Clear reduction in SST bias with resolution in Metis – analysis ongoing
- **Tropical Cyclones**
  - Significant improvements in structure, ACE with resolution
  - Model improvements can lead to better results along with increased resolution
  - Interannual variability of TC frequency still not fully reproducible but improving
- **Project Metis**
  - Clear difference in ensemble mean between 1997/98 and 2015/16 events
    - Large difference in eastern Pacific SST
    - Large difference in north Pacific circulation
  - Clear difference in wet and dry members for 2015/16 event (not shown)
    - Large difference in north Pacific atmospheric circulation, despite relatively minor difference in SST
    - General lack of wet events in dry members
  - Conclusion: Significant forced and unforced differences in north Pacific led to reduced 2015/16 SOCAL rainfall

Implications for Prediction

- Model improvement and increased spatial resolution both can improve skill for forced signal
- Large ensembles needed to assess unforced variance
    - Note: Higher resolution models may demand larger ensembles simply because both signal and noise increase with resolution
- Need to acknowledge unexplained variance in observations