Extremes and climate change : Some Roadblocks to Detection and Attribution

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Detection :

Inadequate sampling of natural variability

- 100-yr trends are very different from shorter-term (~50-yr) trends
- Error bars on tail probabilities are relatively large

Inappropriate null hypotheses

- PDFs of daily anomalies are generally not Gaussian
- Changes in tail probabilities are not related simply to shifts of the mean

Attribution:

Model misrepresentations of climate PDFs and their changes

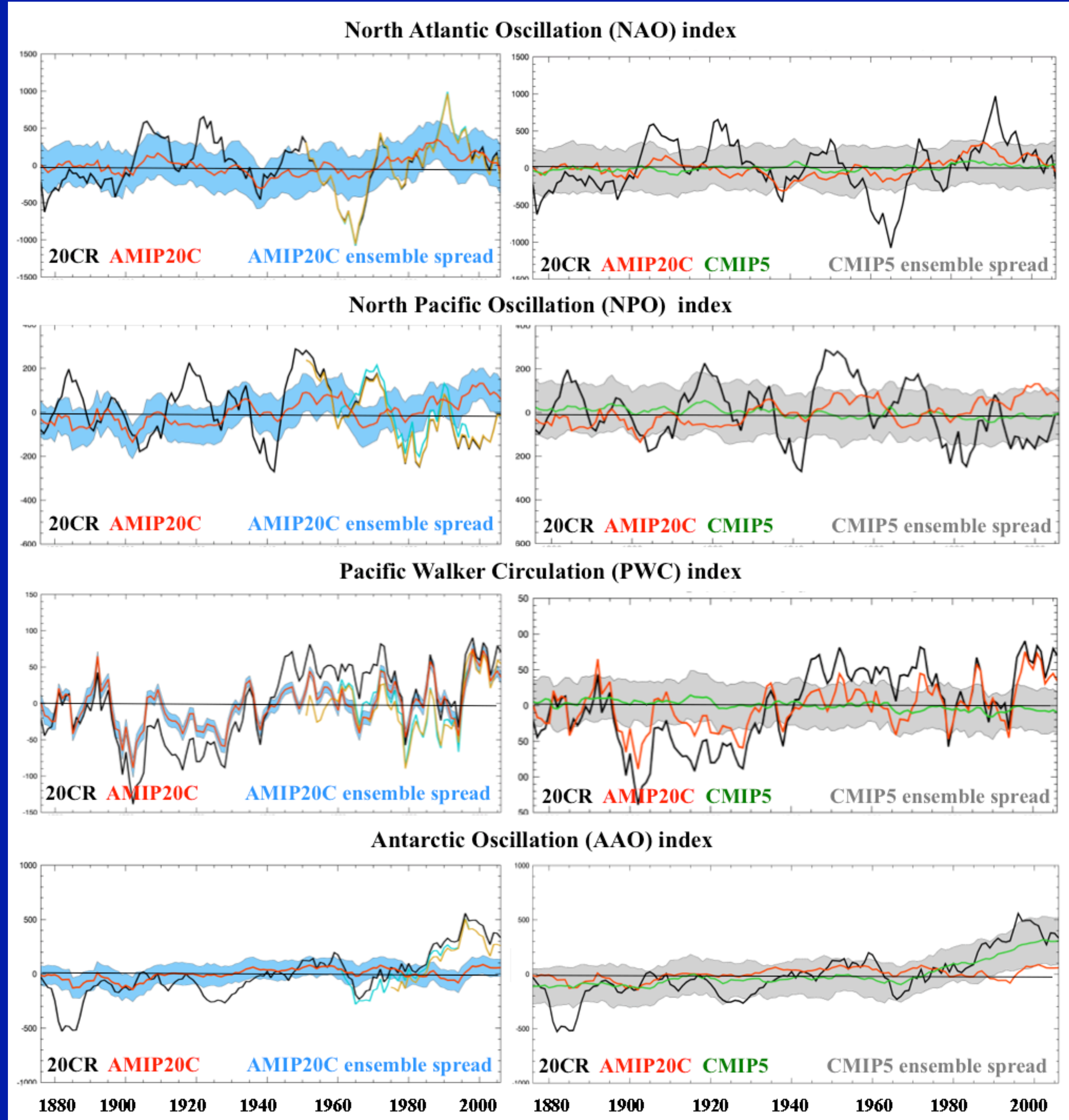
- Mean, Variance, Shape (Skewness, Kurtosis)
- Weak consensus on regional scales, or *False* Consensus

Long-term circulation trends are very different from shorter-term (~ 50-yr) trends.

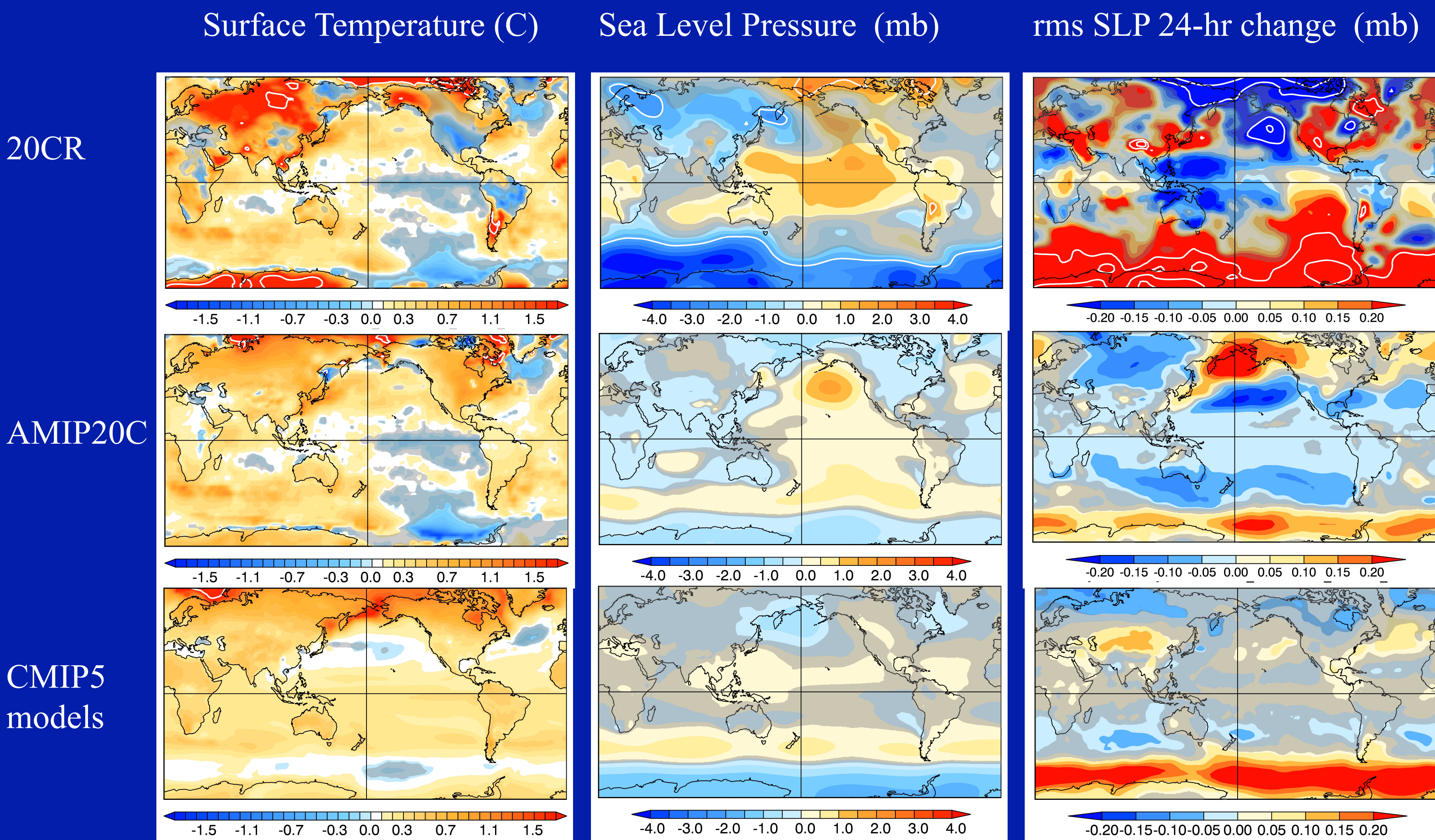
7-yr running means of the **NAO, NPO, PWC,** and **AAO** indices in DJF:

- in the 20th Century Reanalysis **(20CR, BLACK)** and 2 other reanalyses;
- in a 56-member ensemble of AGCM runs **(AMIP20C, RED)** with prescribed observed SSTs and radiative forcings; and
- in CMIP5 coupled model simulations **(GREEN)** with prescribed radiative forcings only.

Note that the 20CR dataset has no significant long-term NAO and NPO trends, and positive PWC and AAO trends.



The generally weak (~ 5%) long-term changes in the mean circulation are associated with even weaker (1%) long-term changes in “storminess” (we define long-term changes here as 1943-2010 minus 1874-1942 DJF averages)



Note that the changes are not significant in the gray shaded areas

The basic difficulty of establishing changes in extreme event statistics ***directly*** from limited climate records

Consider a 200-yr long climate record.

If an event did not occur even once in the first 100 years, and occurred only once in the second 100 years, does this mean that it has become "more likely" ?

Not necessarily.

Return Period N = 1 / probability (by definition; assuming annual events are independent)

The *expected* N is ∞ years from the first period, and 100 years from the second period.
One might therefore be tempted to think that N has decreased from ∞ to 100 years.

But the 90% confidence intervals are $\mathbf{44 < N < \infty}$ and $\mathbf{22 < N < 2000}$ years, respectively.
These are too large for one to conclude that N has changed.
More precisely, there is greater than a 10% chance of no change in N if $\mathbf{80 < N < 800}$ years

Indirect **estimations involve making assumptions about the PDFs, and are prone to** ***Inappropriate Null Hypotheses*****, such as assuming the PDFs are Gaussian when they are not**

This can lead to gross misrepresentations of tail probabilities and their changes

Consider Gaussian vs non-Gaussian PDFs, ***both p(0,1)****, and shifted by 1 sigma*

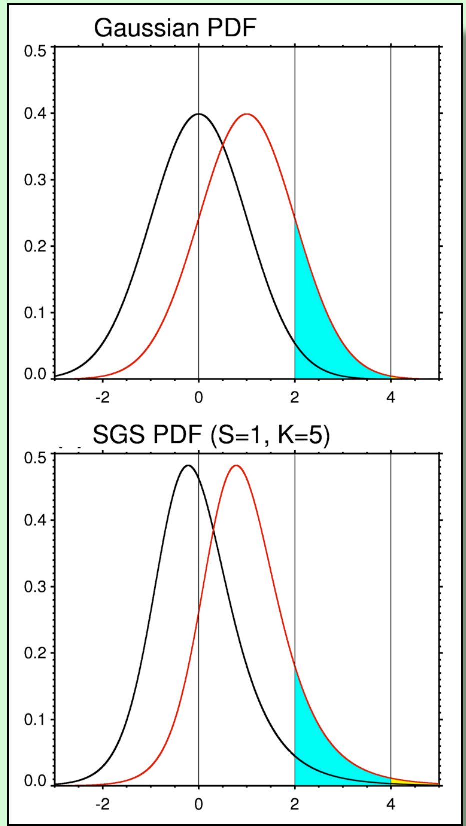
Gaussian PDFs

Non-Gaussian PDFs

skewed and heavy-tailed with

Skewness $S = 1$

Kurtosis $K = 5$



P(x ≥ 2) = 2.3%
and increases by
a factor of 7

P(x ≥ 4) = 0.003%
and increases by
a factor of 43

P(x ≥ 2) = 3.4%
and increases by
only a factor of 4

P(x ≥ 4) = 0.34 %
and increases by
only a factor of 3

In general, climate change involves not just a shift but also changes in the width and shape of the PDF.

In that case, the changes in tail probabilities are not linked simply to the mean shift

For example, a reduced width causes both + and – extremes to decrease, regardless of the shift.

The PDFs of *daily* atmospheric variations are not Gaussian. They are generally skewed and heavy tailed, and in a distinctive way. This has large implications for extreme weather statistics.

Skewness $S = \langle x^3 \rangle / \sigma^3$ and

Kurtosis $K = \langle x^4 \rangle / \sigma^4 - 3$

of wintertime daily anomalies of

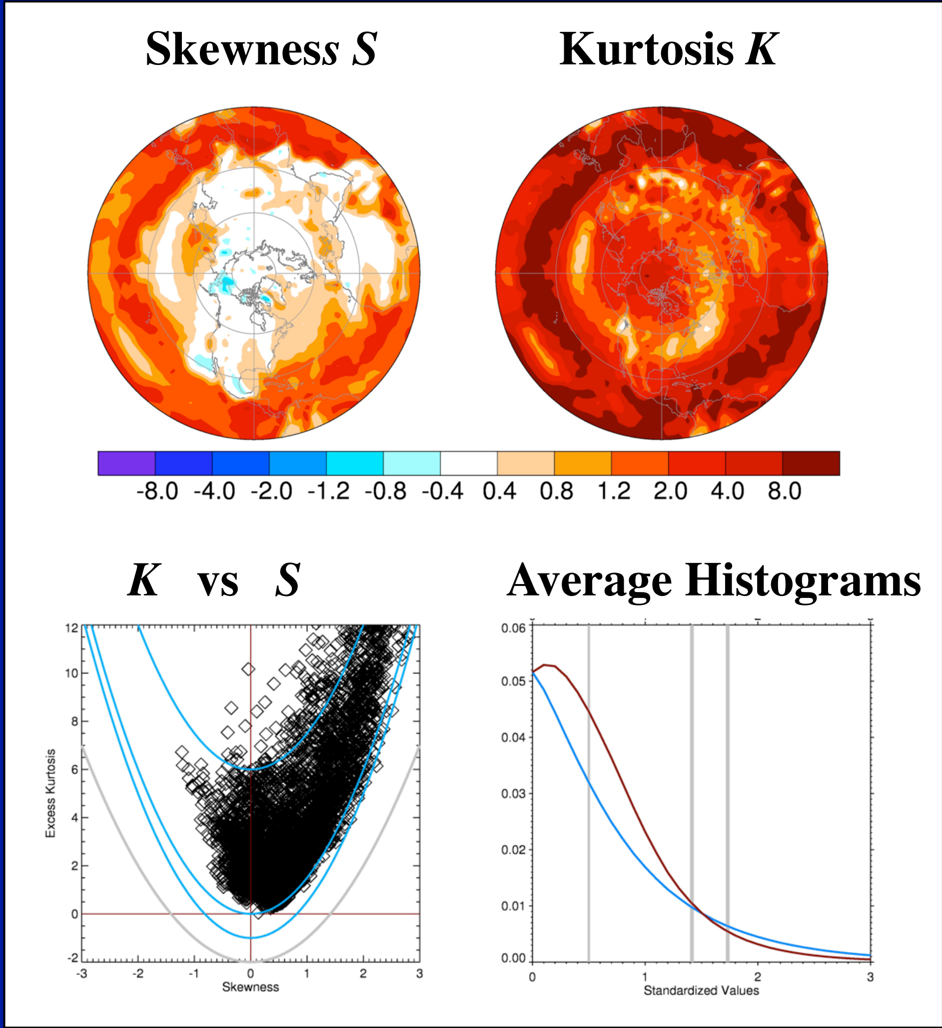
500 mb Vertical Velocity in the

137-yr 20CR dataset (Compo et al 2011)

*These distinctive non-Gaussian features are captured by so-called **Stochastically Generated Skewed ("SGS") distributions***

associated with red noise processes whose stochastic forcing amplitude depends linearly on x as Ex + g

See Sardeshmukh and Sura JClim 2009 for the basic theory

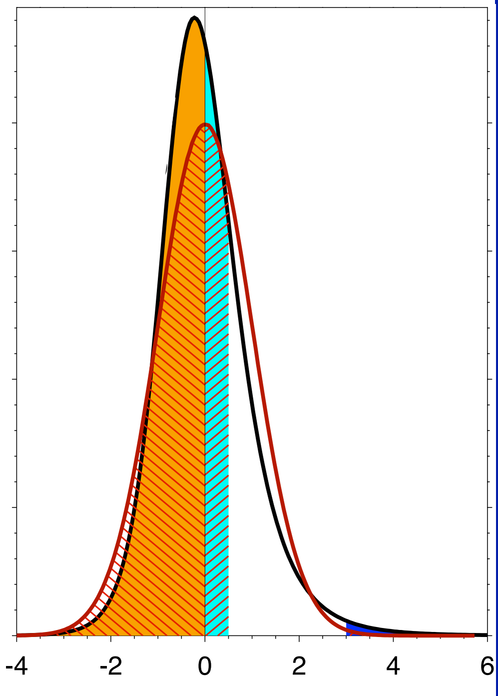


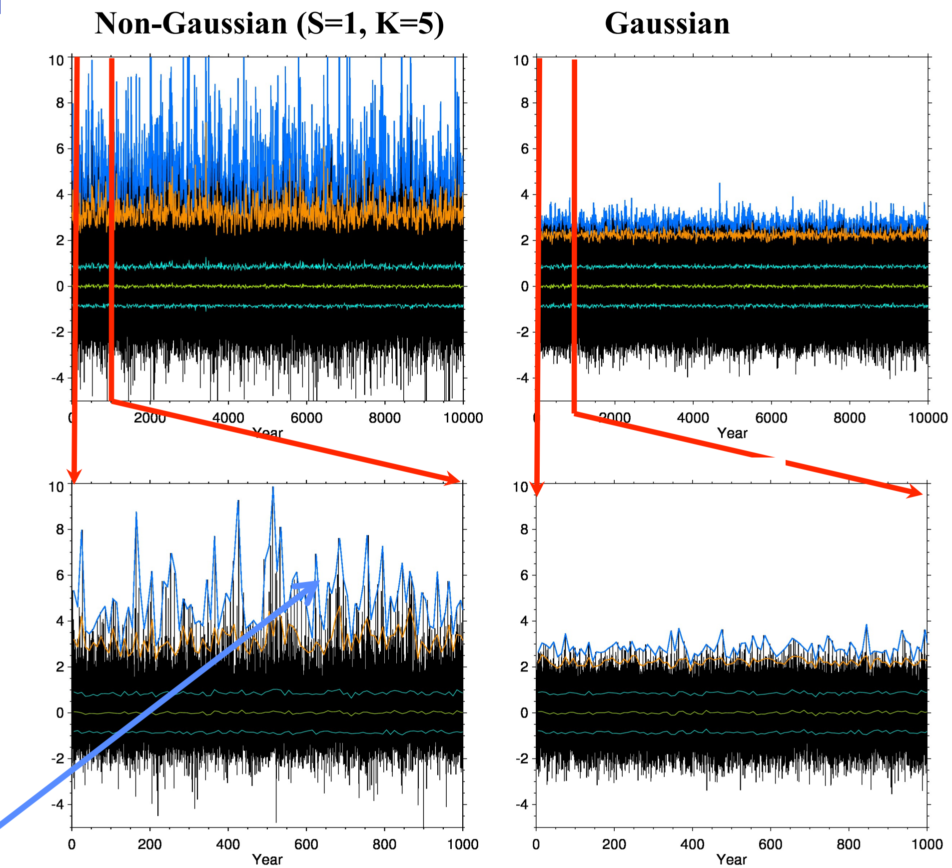
Note the parabolic inequality $K \geq 3/2\, S^2$

Note that the crossover point where $p(x) = p(-x)$ lies between 1.4σ and 1.7σ

Sharply contrasting behavior of extreme anomalies of a red noise process with a 1-day correlation scale obtained in 10^8-day runs (equivalent to 10^6 100-day winters) of the Gaussian and non-Gaussian models

Gaussian (red) and non-Gaussian (black, S=1, K=5) "SGS" PDFs with same mean and variance





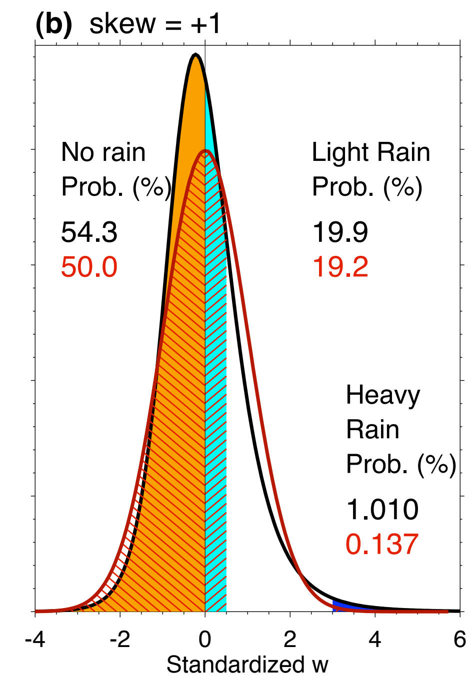
Note how one can obtain spurious 100-yr trends of decadal extremes in the non-Gaussian case ***<u>even in this statistically stationary world</u>*****.**

<u>Blue curves:</u> Time series of decadal maxima (i.e the largest daily anomaly in each decade = 1000 days = 10 100-day winters)

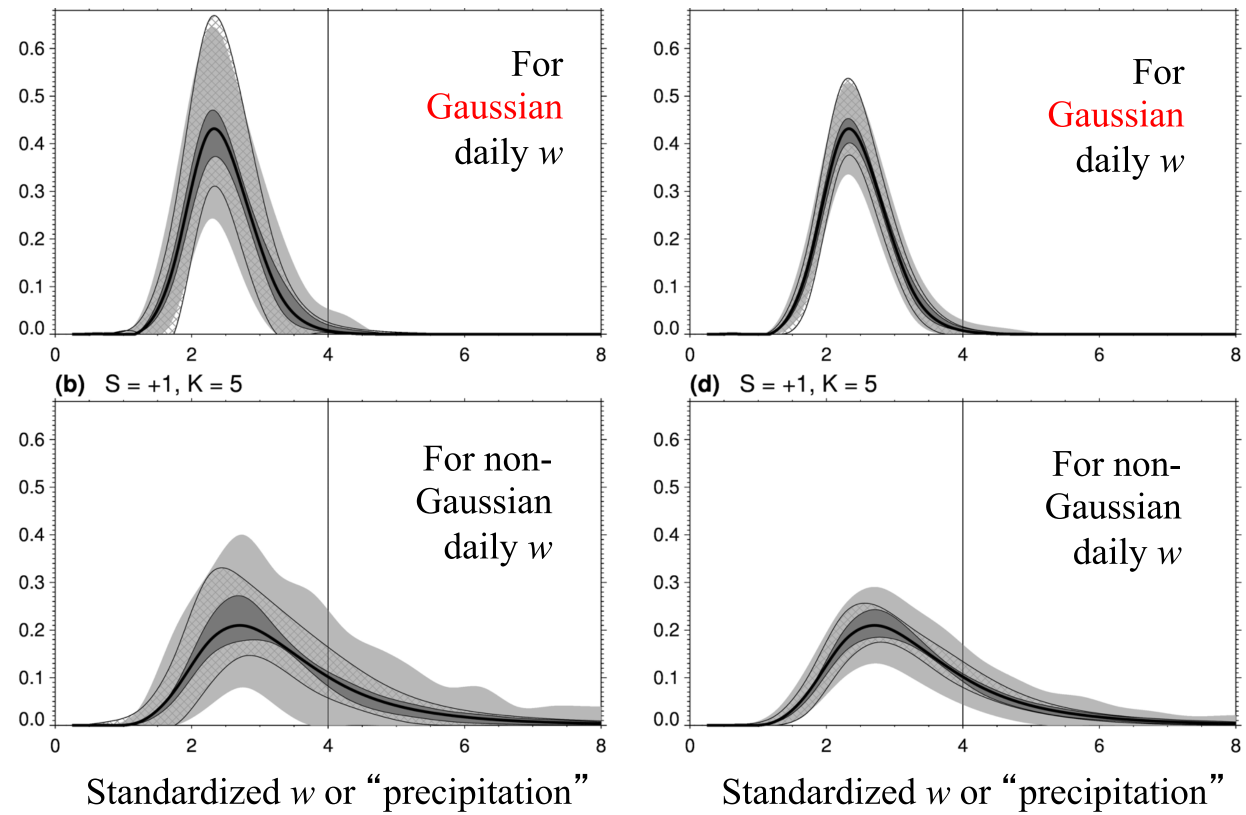
<u>Orange curves</u>: Time series of 99.5th decadal percentile (i.e. the 5th largest daily anomaly in each decade)

The PDFs of winter maxima are VERY DIFFERENT if the PDFs of the daily values are Gaussian or "SGS". They are also more accurately estimated by fitting SGS distributions to *all* daily values than by fitting GEV distributions to just maximum values

PDFs of daily *w* :
Gaussian
and non-Gaussian
(S=1, K=5)



PDFs of daily winter *maxima* (Extreme Value PDFs) estimated using
25-winter records **100-winter records**

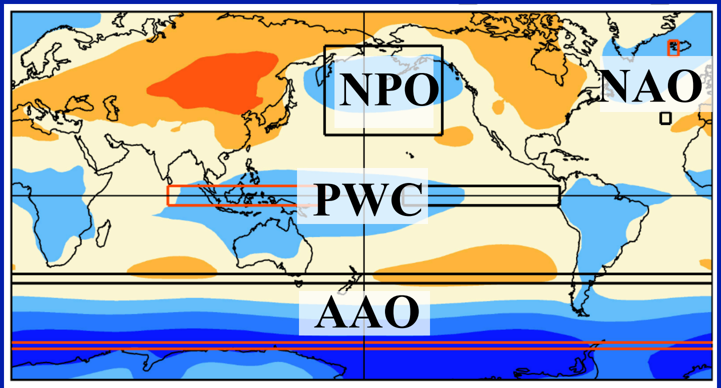


***Black Curves*:** Extreme Value PDFs of winter *w* (or "precipitation") maxima estimated from 10^6 model winters, when the PDF of daily *w* is Gaussian or non-Gaussian

***Shaded bands*:** 95% confidence intervals of estimates from 25- or 100- winter records, based on raw histograms (light gray), GEV (hatched), or SGS (dark grey) distributions

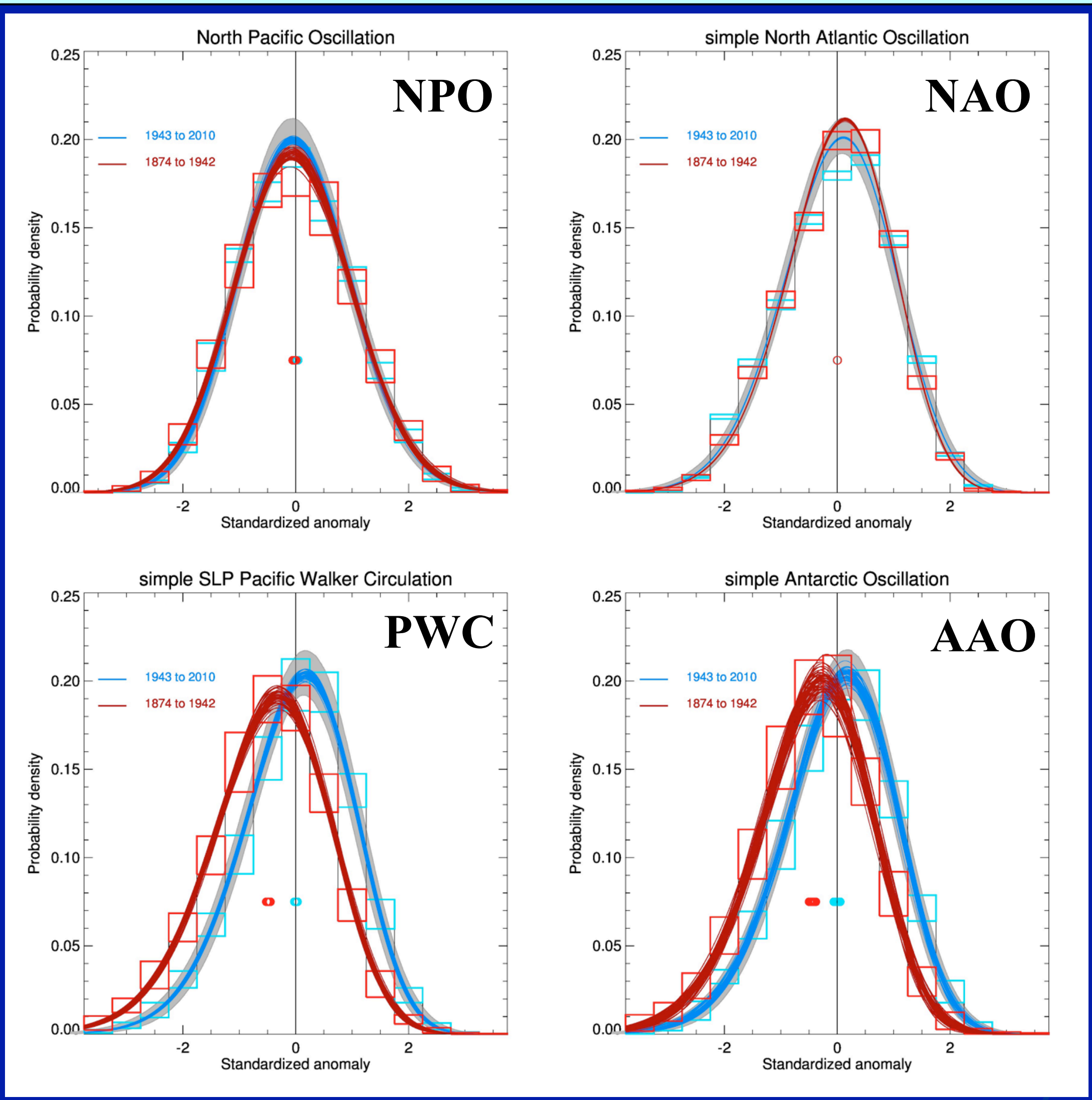
20th century changes in *daily* SLP indices of the North Atlantic Oscillation (**NAO**), North Pacific Oscillation (**NPO**), Pacific Walker Circulation (**PWC**), and the Antarctic Oscillation (**AAO**) in DJF.

MAIN RESULT: ***No Significant Change*** **in the NAO and NPO, and**
A Significant Strengthening **of the PWC and AAO, from 1874-1942 to 1943-2010**



The **blue and red boxes and curves** are raw histograms and "SGS" distributions fitted to each of the 56 20th Century Reanalysis ensemble members. Their spread is measure of *observational uncertainty*,

The grey swath is a measure of *sampling uncertainty* arising from using limited 68-yr records to estimate the PDF. It is derived from Monte Carlo simulations of the process that generates the SGS distribution.



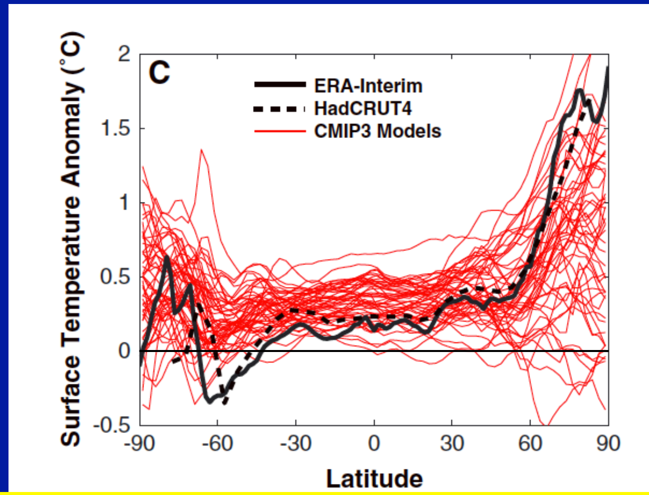
Roadblocks to attribution arising from climate model errors

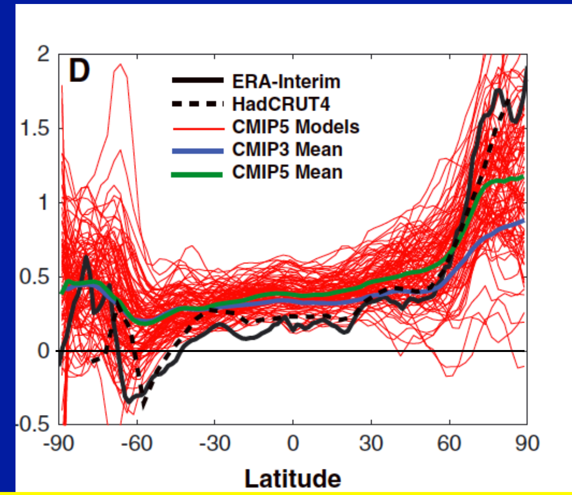
Simulated vs Observed Surface Temperature Change

(2002-2011 average minus 1979-2001 average; *Swanson GRL 2013*)

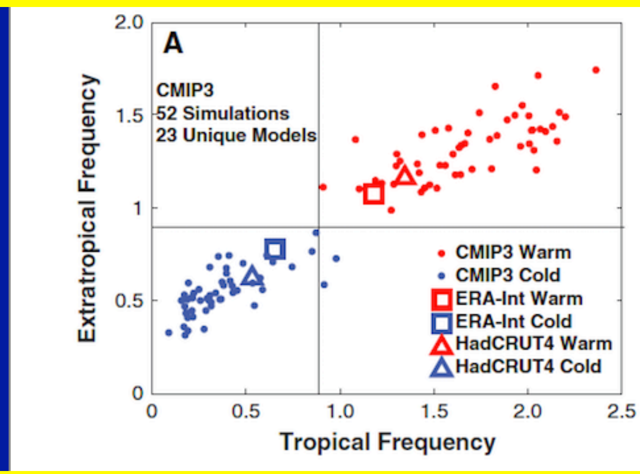
CMIP3 vs OBS

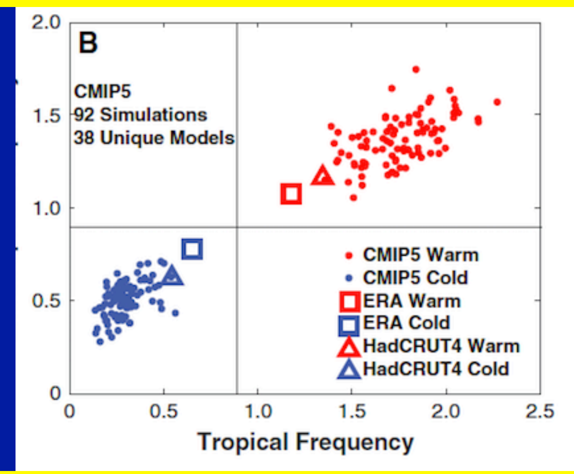
CMIP5 vs OBS





Both CMIP3 and CMIP5 models have clear warming biases in the tropics . . .





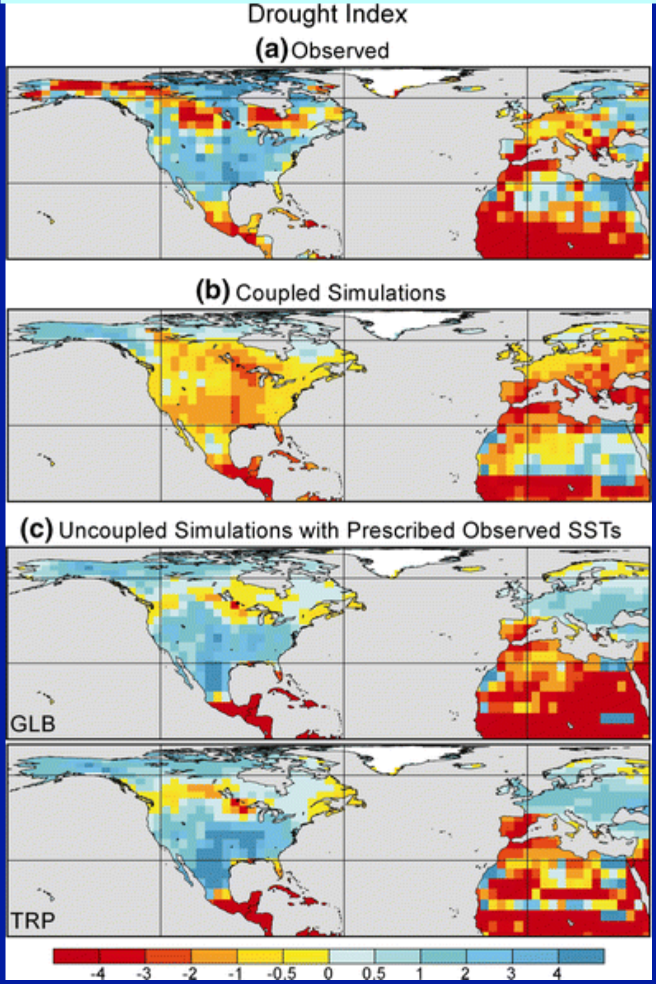
. . . that are associated with overestimated increases of extreme warm months and decreases of extreme cold months, in both the tropics and extratropics

<u>Principal Conclusions from the Shin and Sardeshmukh study (Climate Dynamics 2011)</u> :

1. **In order to get regional-scale climate changes right, it is important to get the tropical SSTs right, even in a radiatively warming world.**

2. **Climate models are not getting the tropical SSTs right.**

Trend of annual Palmer Drought Severity Index (PDSI) over 1951-1999



Blue (Red) shading indicates a trend toward *reduced (increased)* drought

OBS drought trends

COUPLED simulations (CMIP3)

UNCOUPLED simulations (GOGA)

UNCOUPLED simulations (TOGA)

Tropical SST Trends over 1951-1999

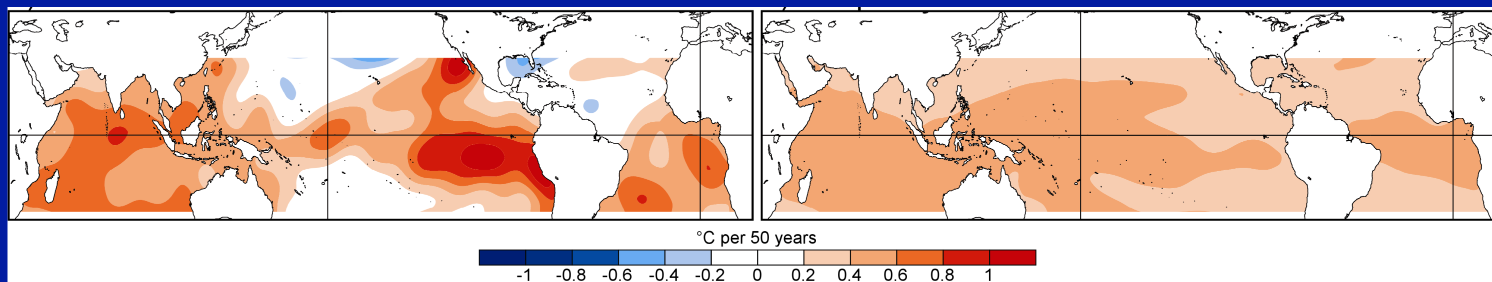
The lower right panel shows that almost all CMIP3 models underestimated the spatial variation of the observed trends

OBSERVED TREND

(average of 3 datasets)

SIMULATED TREND

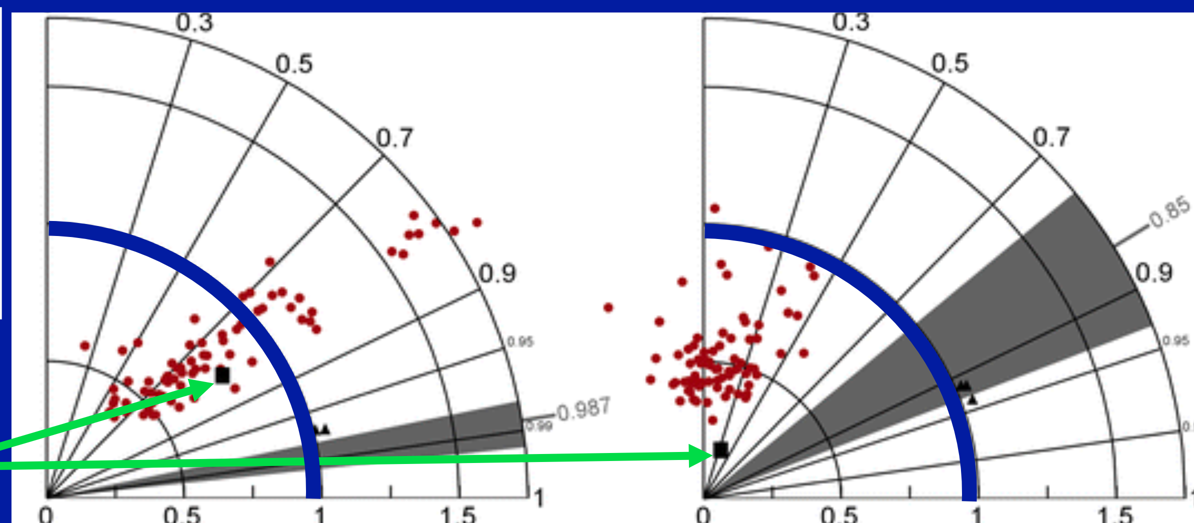
(average of 76 coupled CMIP3 simulations)



INCLUDING area-mean trends

EXCLUDING area-mean trends

Fidelity of all 76 CMIP3 simulated SST trend fields



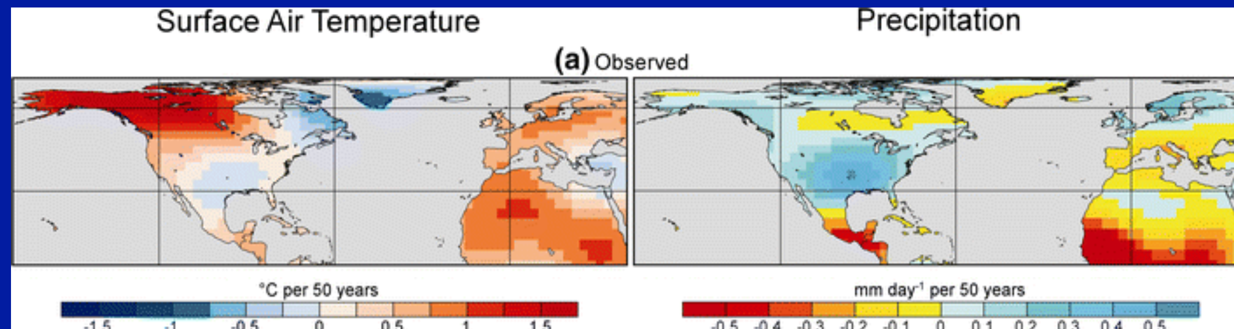
MME-mean trend

Shin and Sardeshmukh 2011

The *spatial pattern* of the tropical SST warming really does matter !

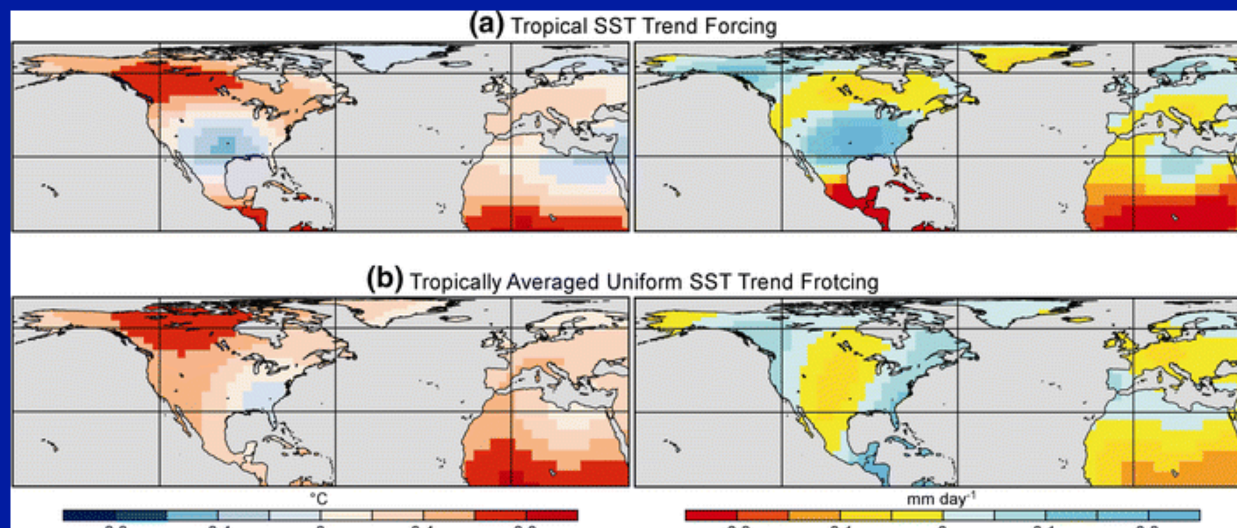
Observed and simulated regional climate trends over 1951-1999

Observed Trends



Simulated uncoupled ECHAM5 model responses :

- To prescribed observed tropical SST trend forcing
- To prescribed spatially uniform portion of the observed tropical SST trend forcing



Shin and Sardeshmukh 2011

Will increasing model resolution improve the representation of extremes ?

Not necessarily . . .

Consider the following results from medium (T159) to high (T2047) resolution runs in project ATHENA (Jung et al 2012, Kinter et al 2013)

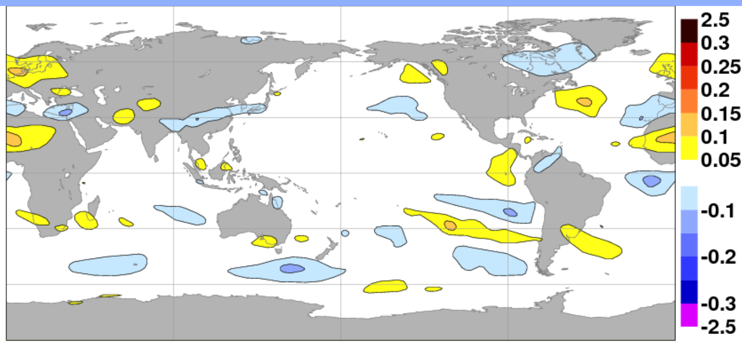
+ additional T95 resolution runs

- 1989-2007 (1 run per year, 1 ensemble member)
- These are AMIP runs
- We focus here on the DJF season

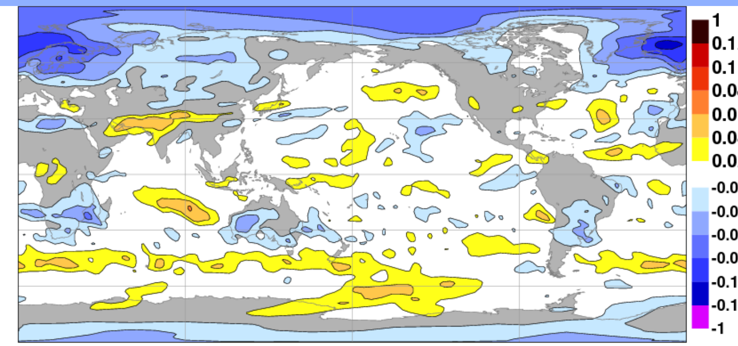
Magnusson and Sardeshmukh 2015

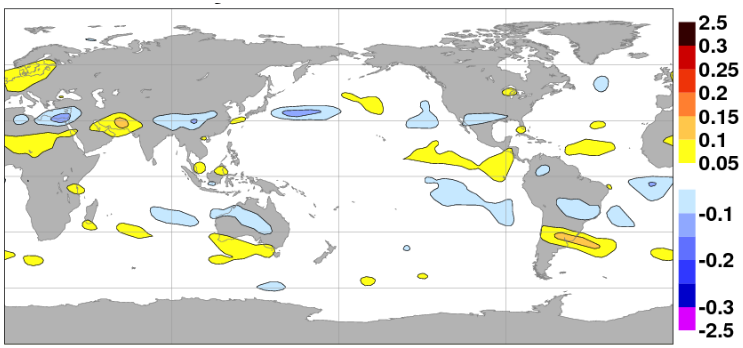
Biases in DJF mean and daily standard deviation of 200 mb Vorticity

Biases in mean		Biases in Standard Deviation

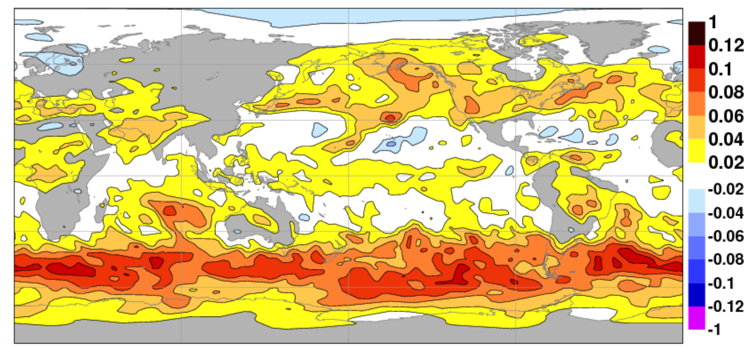


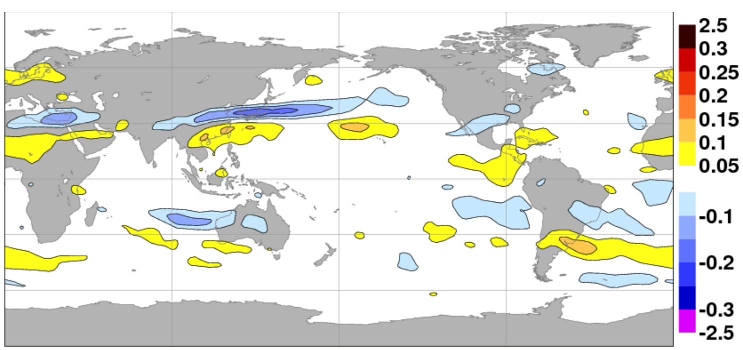
T95



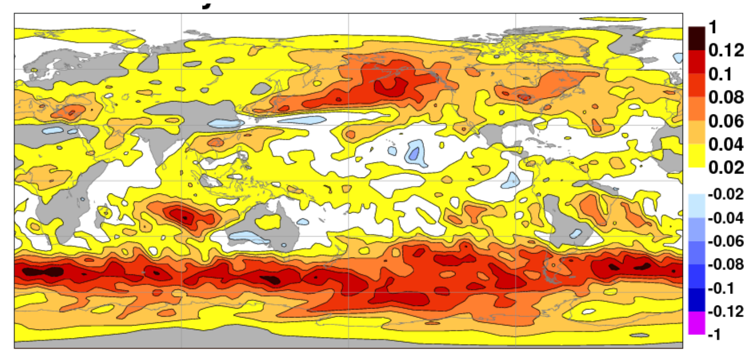


T511





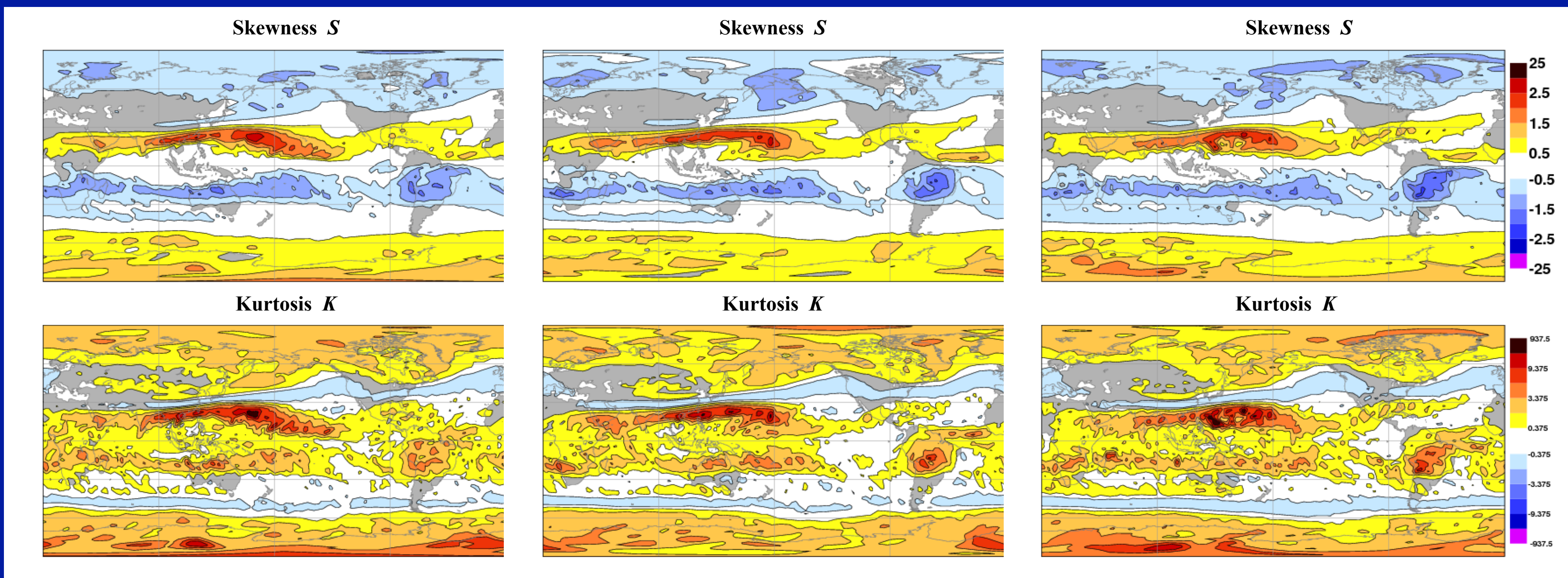
T2047



Skewness *S* and Kurtosis *K* of daily 200 mb Vorticity in DJF

***S* and *K* remain nearly identical (and realistic) over a 20-fold increase of resolution !**

ERA Interim | T95 | T2047



NOTE also that the color scale for *K* is $3/2\ x^2$ times the color scale x for *S*

This allows easy visual confirmation of the parabolic *K*-*S* relationship for atmospheric variability

Extremes and climate change : Some Roadblocks to Detection and Attribution

and some possible ways around them

<u>Detection</u> :

Inadequate sampling of natural variability

- 100-yr trends are very different from shorter-term (~50-yr) trends
- Error bars on tail probabilities are relatively large

Development of long-term observational and reanalysis datasets ?

Inappropriate null hypotheses

- PDFs of daily anomalies are generally not Gaussian
- Changes in tail probabilities are not related simply to shifts of the mean

Development of multivariate non-Gaussian Probability Models ?
(Could be simple models or comprehensive high-resolution AGCMs)

<u>Attribution</u>:

Model misrepresentations of climate PDFs and their changes

- Mean, Variance, Shape (Skewness, Kurtosis)
- Weak consensus on regional scales, or *False* Consensus

Reducing tropical SST errors ?
Reducing variance biases through a proper balancing of deterministic and stochastic parameterizations ?

Extra Slides

A simple mechanism for generating skewed heavy-tailed probability distributions
("Stochastically Generated Skewed (SGS) distributions" *Sardeshmukh and Sura J. Clim 2009*)

$$\frac{dx}{dt} = -\left(\lambda + \frac{1}{2}E^2\right)x + b\,\eta_1 + (Ex+g)\eta_2 - \frac{1}{2}Eg$$

where b and g are amplitudes of "additive" noise, and E is amplitude of "multiplicative" noise

If $E \to 0$ *then pdf* $p(x)$ *of* $x \to$ *Gaussian pdf*

If $E \neq 0$ *then* $p(x)$ *is skewed and heavy-tailed, with* $K > \frac{3}{2}S^2$ *and* $p(x) = p(-x)$ *at* $\hat{x} \approx \sqrt{3}\sigma$

$$\text{Mean} \quad \mu = \langle x \rangle = 0$$

$$\text{Variance} \quad \sigma^2 = \langle x^2 \rangle = \frac{g^2 + b^2}{2\lambda(1-\alpha)} \qquad \text{where } \alpha \equiv \frac{E^2}{2\lambda} \quad \left(< \frac{1}{3} \text{ if Kurtosis exists}\right)$$

$$\text{Skewness} \quad S = \frac{\langle x^3 \rangle}{\sigma^3} = \frac{2E}{\lambda(1-2\alpha)}\frac{g}{\sigma}$$

$$\text{Kurtosis} \quad K = \frac{\langle x^4 \rangle}{\sigma^4} - 3 = \frac{3}{2}\left[\frac{1-2\alpha}{1-3\alpha}\right]S^2 + \frac{6\alpha}{[1-3\alpha]} > \frac{3}{2}S^2$$

Why are Skewness and Kurtosis unaffected by increases of model resolution ?

Is this because increasing model resolution basically just adds <u>additive</u> noise ?

$$\frac{dx}{dt} = -\left(\lambda + \frac{1}{2}E^2\right)x + b\,\eta_1 + (Ex+g)\eta_2 - \frac{1}{2}Eg$$

where b and g are amplitudes of "additive" noise, and E is amplitude of "multiplicative" noise

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NOTE THAT if we change the additive noise forcing by a factor θ,

so that $b \to \theta b$ *and* $g \to \theta g$, *then* $\sigma \to \theta\sigma$, *but S and K are unchanged !*