Likelihood and predictability of cooling episodes in a warming climate

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Introduction

- Earth's climate subject to "natural" (unforced) variability
  - range of time scales
  - regionally dependent

- Superimposed on anthropogenically-forced warming
  $\Rightarrow$ *transient cooling may occur despite warming trend*

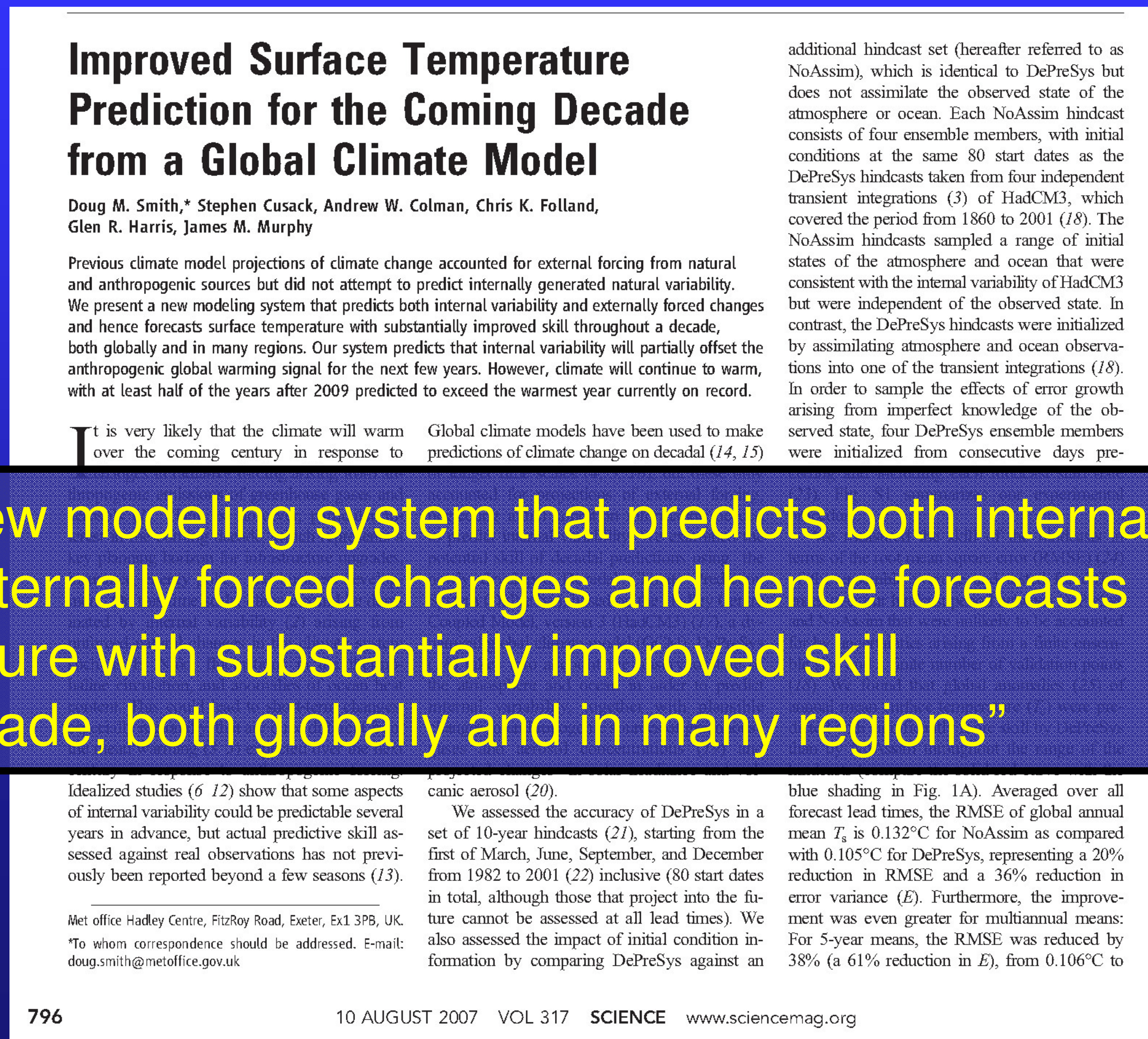
- How frequent are such events given
  - magnitude of warming trend
  - length of interval
  - region considered ?

"The climate system will also exhibit long timescale internally generated variability during the 21st century which may either enhance or retard the forced climate change locally and globally. ***Both forced and internally generated components must be considered in climate forecasts for the next decade or decades***."

- Boer, 2009, *Decadal potential predictability of 21st century climate*, submitted

Decadal Prediction

- Smith et al. *Science* (2007)



Improved Surface Temperature Prediction for the Coming Decade from a Global Climate Model

Doug M. Smith,* Stephen Cusack, Andrew W. Colman, Chris K. Folland, Glen R. Harris, James M. Murphy

Previous climate model projections of climate change accounted for external forcing from natural and anthropogenic sources but did not attempt to predict internally generated natural variability. We present a new modeling system that predicts both internal variability and externally forced changes and hence forecasts surface temperature with substantially improved skill throughout a decade, both globally and in many regions. Our system predicts that internal variability will partially offset the anthropogenic global warming signal for the next few years. However, climate will continue to warm, with at least half of the years after 2009 predicted to exceed the warmest year currently on record.

It is very likely that the climate will warm over the coming century in response to

Idealized studies (6–12) show that some aspects of internal variability could be predictable several years in advance, but actual predictive skill assessed against real observations has not previously been reported beyond a few seasons (13).

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Global climate models have been used to make predictions of climate change on decadal (14, 15)

canic aerosol (20).

We assessed the accuracy of DePreSys in a set of 10-year hindcasts (21), starting from the first of March, June, September, and December from 1982 to 2001 (22) inclusive (80 start dates in total, although those that project into the future cannot be assessed at all lead times). We also assessed the impact of initial condition information by comparing DePreSys against an

additional hindcast set (hereafter referred to as NoAssim), which is identical to DePreSys but does not assimilate the observed state of the atmosphere or ocean. Each NoAssim hindcast consists of four ensemble members, with initial conditions at the same 80 start dates as the DePreSys hindcasts taken from four independent transient integrations (3) of HadCM3, which covered the period from 1860 to 2001 (18). The NoAssim hindcasts sampled a range of initial states of the atmosphere and ocean that were consistent with the internal variability of HadCM3 but were independent of the observed state. In contrast, the DePreSys hindcasts were initialized by assimilating atmosphere and ocean observations into one of the transient integrations (18). In order to sample the effects of error growth arising from imperfect knowledge of the observed state, four DePreSys ensemble members were initialized from consecutive days pre-

blue shading in Fig. 1A). Averaged over all forecast lead times, the RMSE of global annual mean T_s is 0.132°C for NoAssim as compared with 0.105°C for DePreSys, representing a 20% reduction in RMSE and a 36% reduction in error variance (E). Furthermore, the improvement was even greater for multiannual means: For 5-year means, the RMSE was reduced by 38% (a 61% reduction in E), from 0.106°C to

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content. This could lead to short-term changes, especially regionally, that are quite different from the mean warming (3–5) expected over the next century in response to anthropogenic forcing. Idealized studies (6–12) show that some aspects of internal variability could be predictable several years in advance, but actual predictive skill assessed against real observations has not previously been reported beyond a few seasons (13).

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internal variability, together with plausible changes in anthropogenic sources of greenhouse gases and aerosol concentrations (19) and projected changes in solar irradiance and volcanic aerosol (20).

We assessed the accuracy of DePreSys in a set of 10-year hindcasts (21), starting from the first of March, June, September, and December from 1982 to 2001 (22) inclusive (80 start dates in total, although those that project into the future cannot be assessed at all lead times). We also assessed the impact of initial condition information by comparing DePreSys against an additional hindcast set (hereafter referred to as NoAssim), which is identical to DePreSys but does not assimilate the observed state of the atmosphere or ocean. Each NoAssim hindcast consists of four ensemble members, with initial conditions at the same 80 start dates as the DePreSys hindcasts taken from four independent transient integrations (3) of HadCM3, which covered the period from 1860 to 2001 (18). The NoAssim hindcasts sampled a range of initial states of the atmosphere and ocean that were consistent with the internal variability of HadCM3 but were independent of the observed state. In contrast, the DePreSys hindcasts were initialized by assimilating atmosphere and ocean observations into one of the transient integrations (18). In order to sample the effects of error growth arising from imperfect knowledge of the observed state, four DePreSys ensemble members were initialized from consecutive days pre-

annual mean surface temperature (T_s) were predicted with significantly more skill by DePreSys than by NoAssim throughout the range of the hindcasts (compare the solid red curve with the blue shading in Fig. 1A). Averaged over all forecast lead times, the RMSE of global annual mean T_s is 0.132°C for NoAssim as compared with 0.105°C for DePreSys, representing a 20% reduction in RMSE and a 36% reduction in error variance (E). Furthermore, the improvement was even greater for multiannual means: For 5-year means, the RMSE was reduced by 38% (a 61% reduction in E), from 0.106°C to

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Decadal Prediction

- Keenlyside et al. *Nature* (2008)

nature Vol 453|1 May 2008|**doi:10.1038/nature06921**

LETTERS

Advancing decadal-scale climate prediction in the North Atlantic sector

N. S. Keenlyside[1], M. Latif[1], J. Jungclaus[2], L. Kornblueh[2] & E. Roeckner[2]

The climate of the North Atlantic region exhibits fluctuations on decadal timescales that have large societal consequences. Prominent examples include hurricane activity in the Atlantic[1],

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and North American surface temperatures will cool slightly, whereas tropical Pacific SST will remain almost unchanged. Our results suggest that global surface temperature may not increase over the next decade, as natural climate variations in the North Atlantic and tropical Pacific temporarily offset the projected anthropogenic warming.

The North Atlantic is a region with large natural multidecadal variability[2,4,11–14]. Observations suggest that Atlantic multidecadal variability may be oscillatory, with a period of 70–80 years. Palaeo-

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"…we make the following forecast: over the next decade, the current Atlantic meridional overturning circulation will weaken to its long-term mean; moreover, North Atlantic SST and European and North American surface temperatures will cool slightly"

Decadal Prediction

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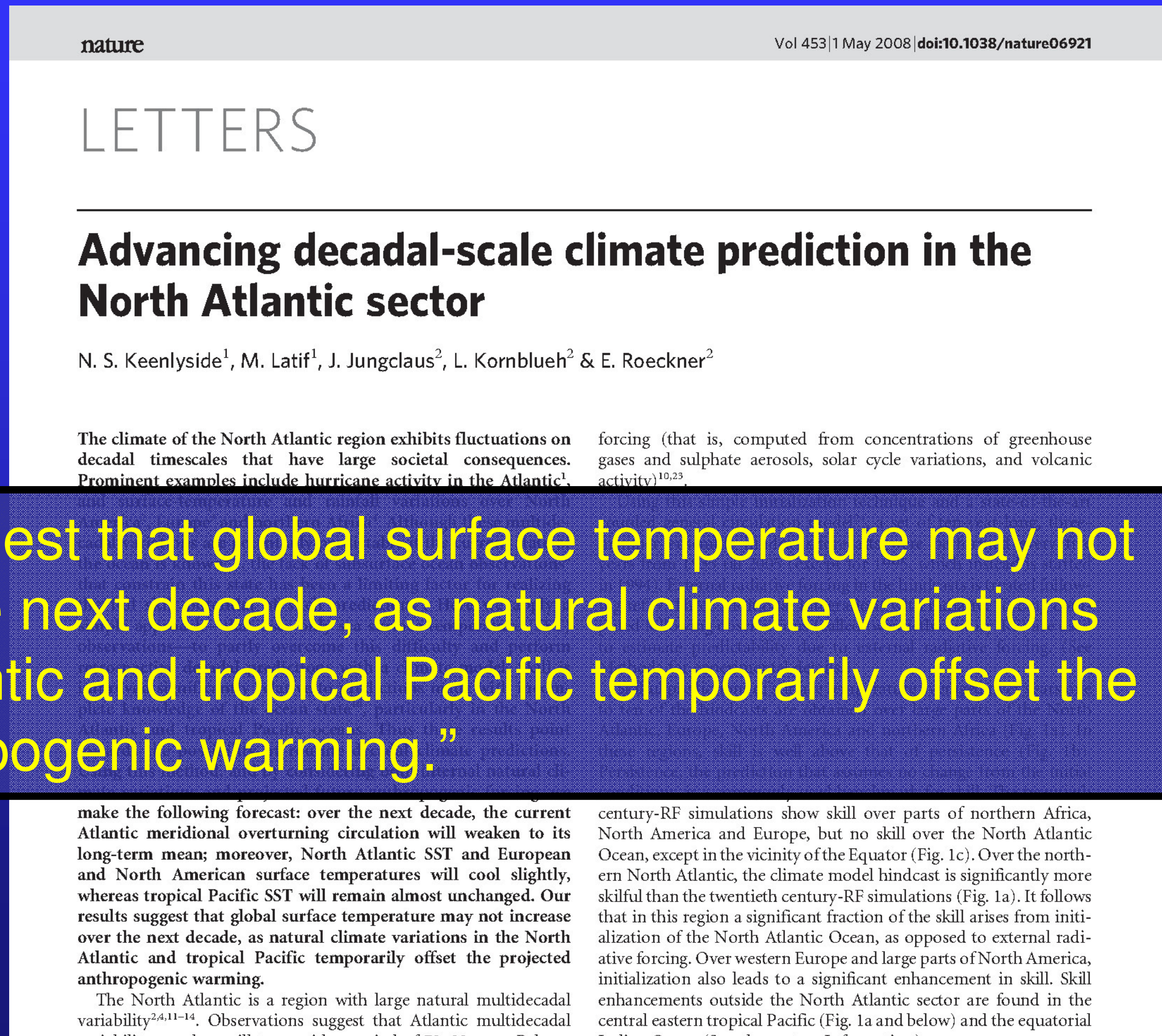

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century-RF simulations show skill over parts of northern Africa, North America and Europe, but no skill over the North Atlantic Ocean, except in the vicinity of the Equator (Fig. 1c). Over the northern North Atlantic, the climate model hindcast is significantly more skilful than the twentieth century-RF simulations (Fig. 1a). It follows that in this region a significant fraction of the skill arises from initialization of the North Atlantic Ocean, as opposed to external radiative forcing. Over western Europe and large parts of North America, initialization also leads to a significant enhancement in skill. Skill enhancements outside the North Atlantic sector are found in the central eastern tropical Pacific (Fig. 1a and below) and the equatorial Indian Ocean (Supplementary Information).

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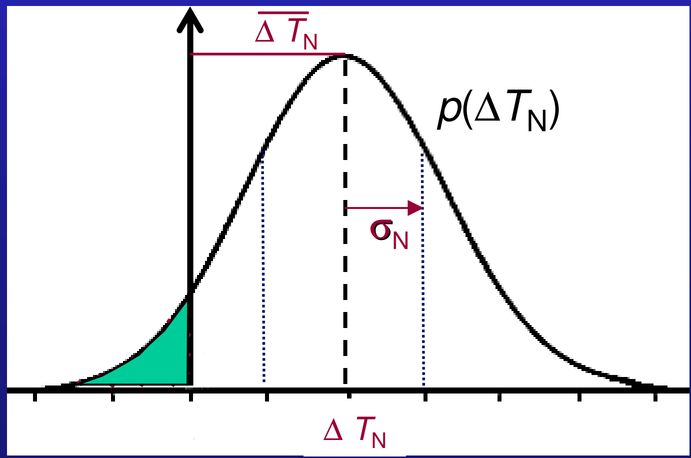
Approach

- Diagnose probability P_N that the next N-year mean $\langle T_N \rangle_{m+1}$ will be *cooler* than the preceding N-year mean $\langle T_N \rangle_m$
- CMIP5 ensemble: B2, A1B scenarios
- Consider both regionally and globally
- Compare with results from autoregressive model

Conceptual framework

- Consider probability density $p(\Delta T_N)$ for the ***difference*** between successive N-year means
- If $p(\Delta T_N)$ is Gaussian then $p \propto \exp - \frac{(\Delta T_N - \overline{\Delta T_N})^2}{2\sigma_N^2}$
- Then cooling probability P_N is the conditional probability that $\Delta T_N < 0$:

$$P_N = \int_{-\infty}^{0} p(\Delta T_N)\,d(\Delta T_N)$$



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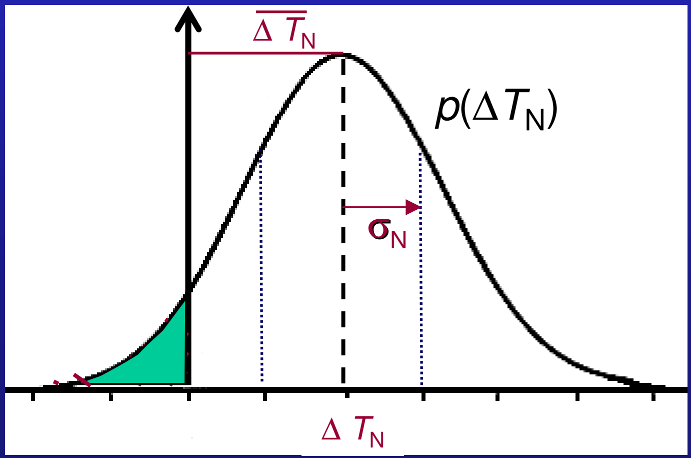
$$P_N = \int_{-\infty}^{0} p(\Delta T_N) d(\Delta T_N)$$

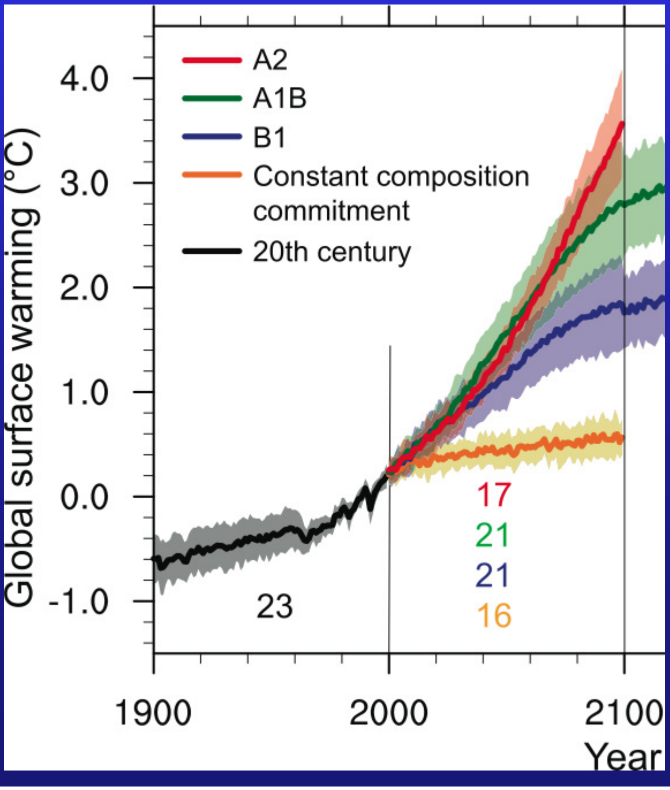
$$= \tfrac{1}{2}[1 + \mathrm{erf}(-\overline{\Delta T_N} / \sigma_N \sqrt{2})]$$



Results from the CMIP3 ensemble

- Consider years 2000-2099
  - B1 scenario: 20 models, 48 runs, 4800 years
  - A1B scenario: 12 models, 12 runs, 1200 years

- ΔT trends "reasonably" uniform over 21st century



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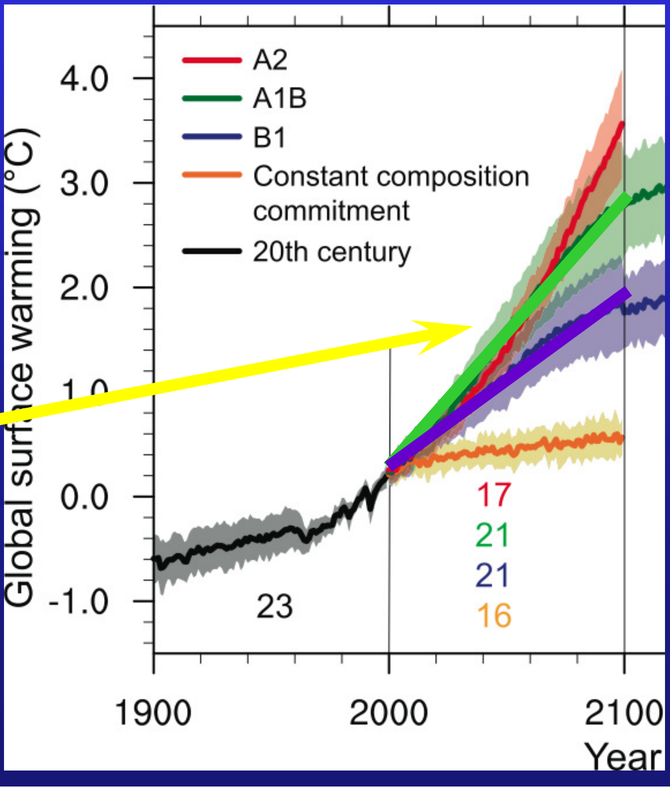
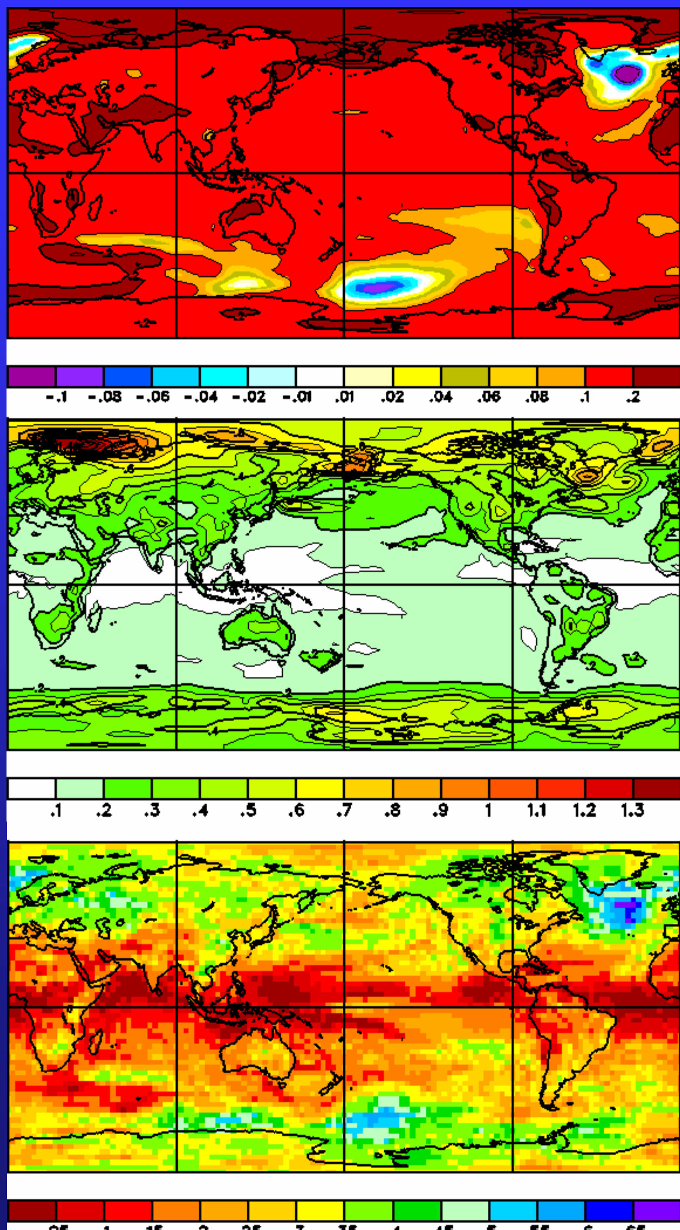
approximately linear trends



Example

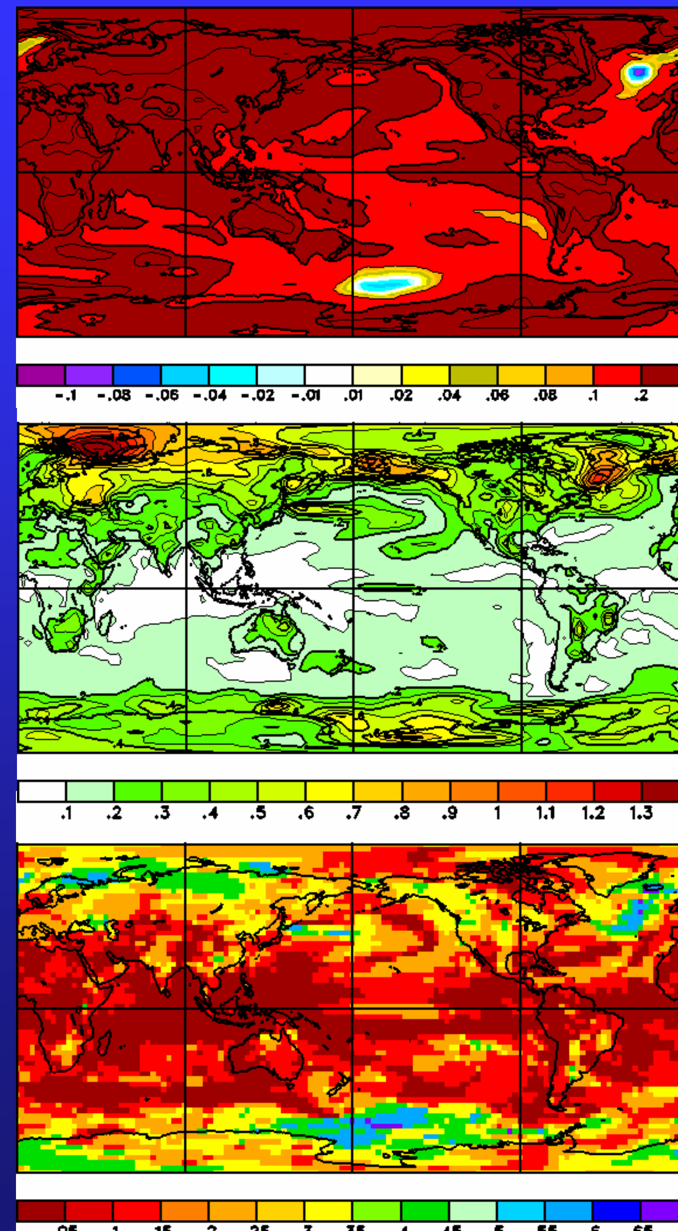
B1 **CCCma CGCM3.1 (T47)** N=10 A1B



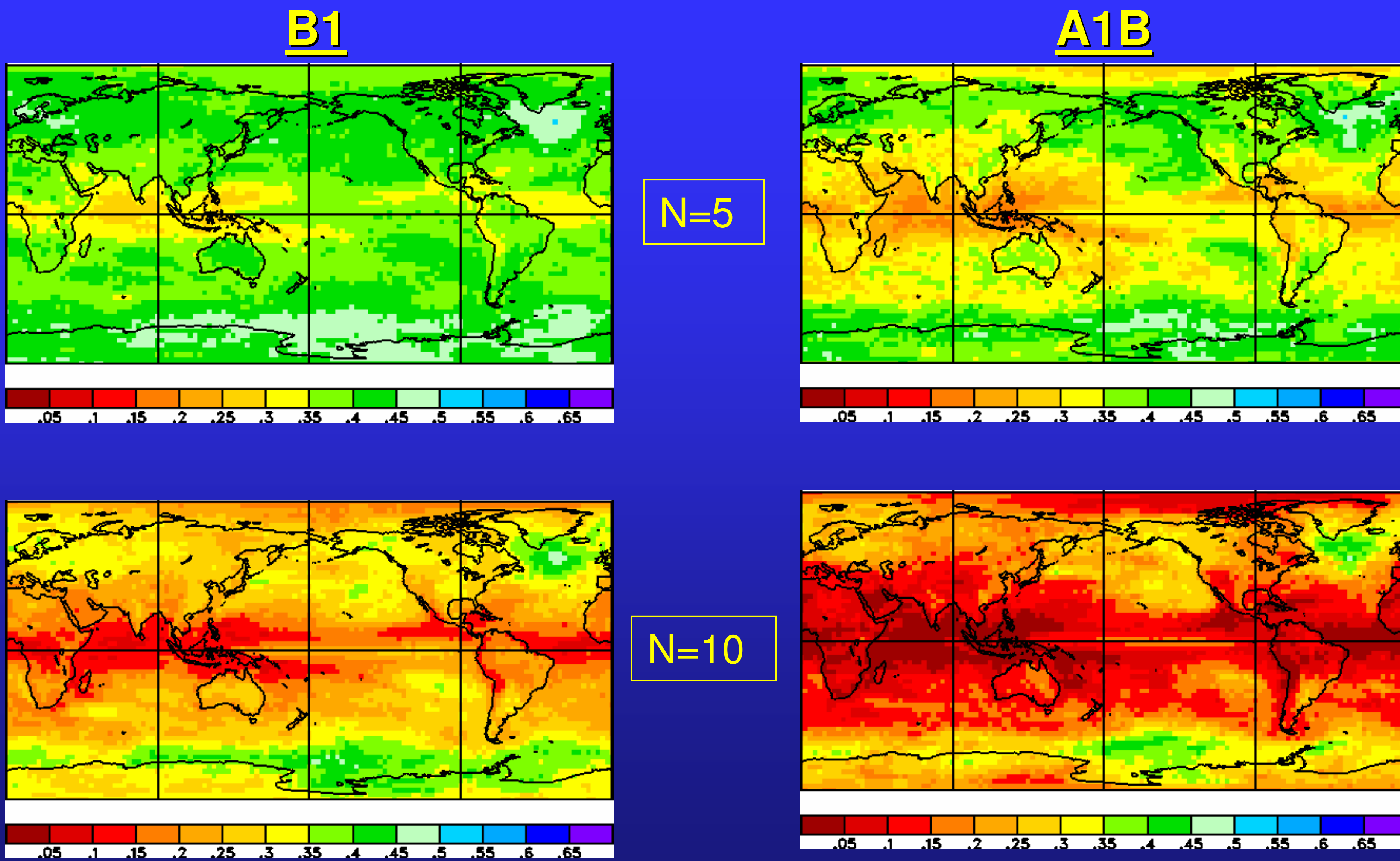
$\overline{\Delta T_N}$

σ_N

P_N



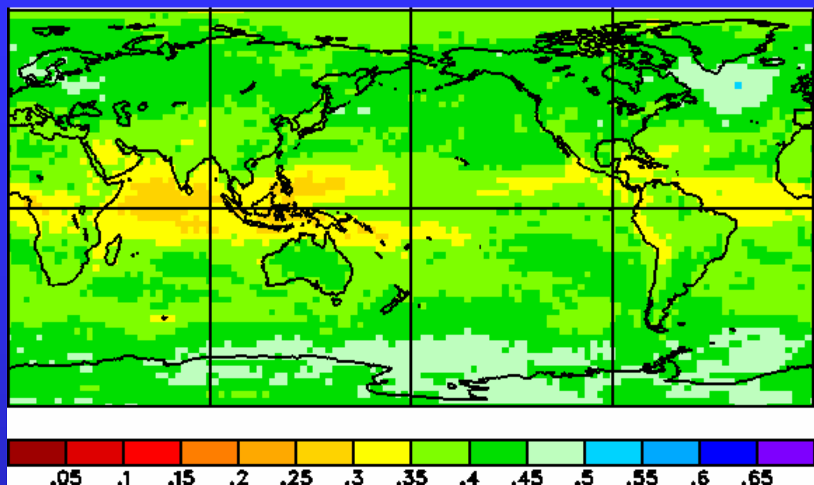
Multi-model average P_N

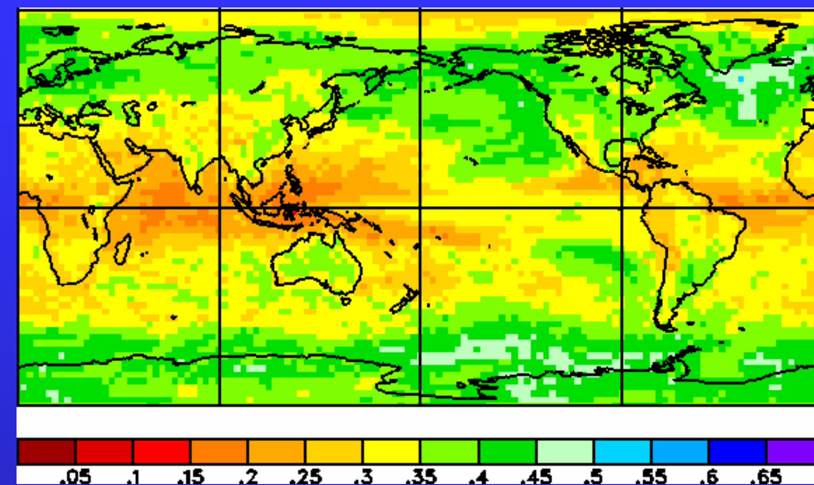


Multi-model average P_N

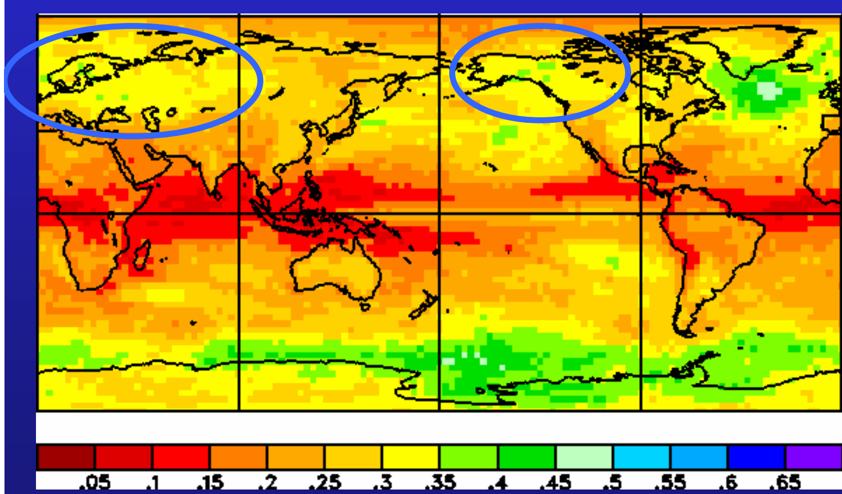
B1 / A1B

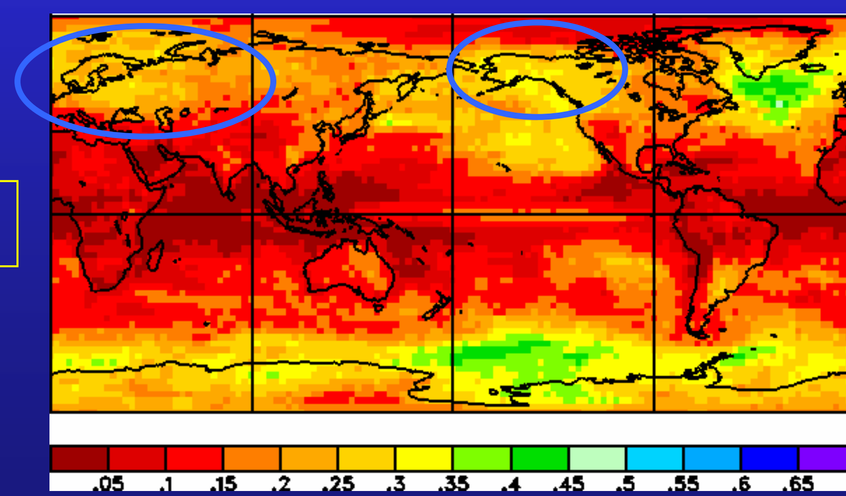
N=5





N=10





How well can P_N be predicted from ΔT_N & σ_N ?

- Recall $$P_N = \int_{-\infty}^{0} p(\Delta T_N)\,d(\Delta T_N)$$
  $$= \tfrac{1}{2}[1 + \mathrm{erf}(-\Delta T_N / \sigma_N\sqrt{2})] \qquad (1)$$

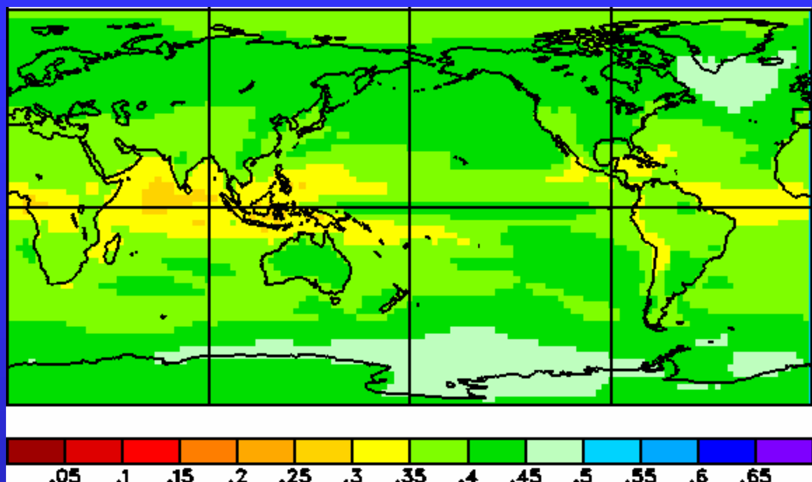
  which applies for a Gaussian pdf

- P_N depends solely on $\Delta T_N / \sigma_N$

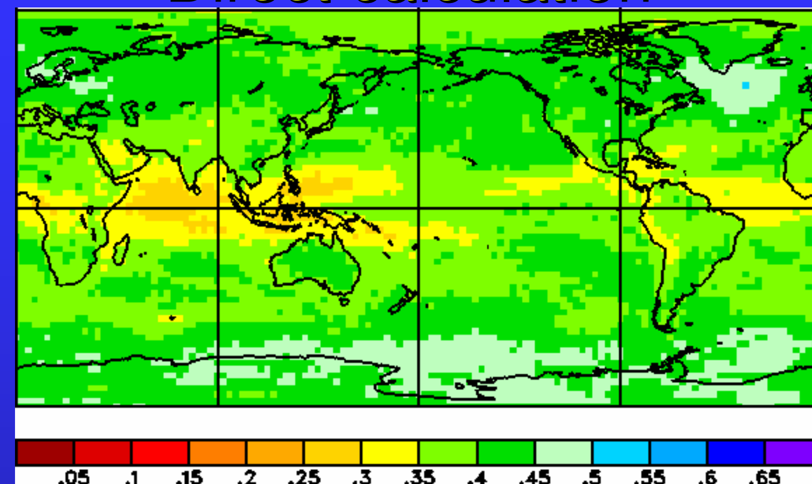
Multi-model P_N (B1)

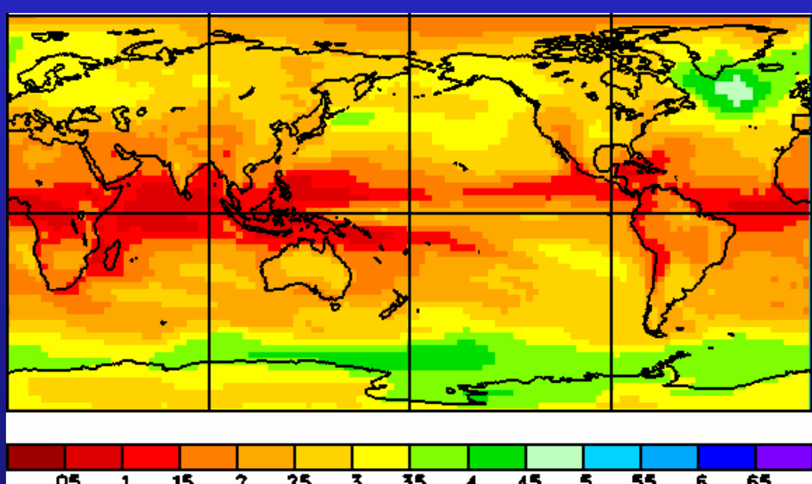
From (1)

Direct calculation



N=5





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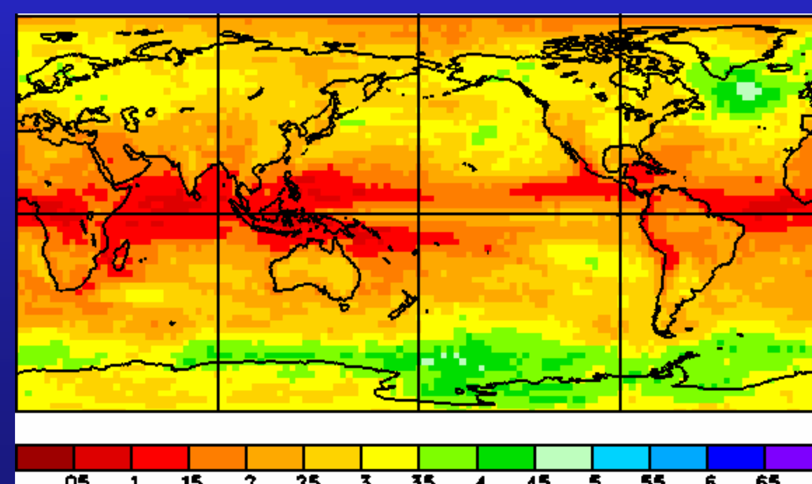
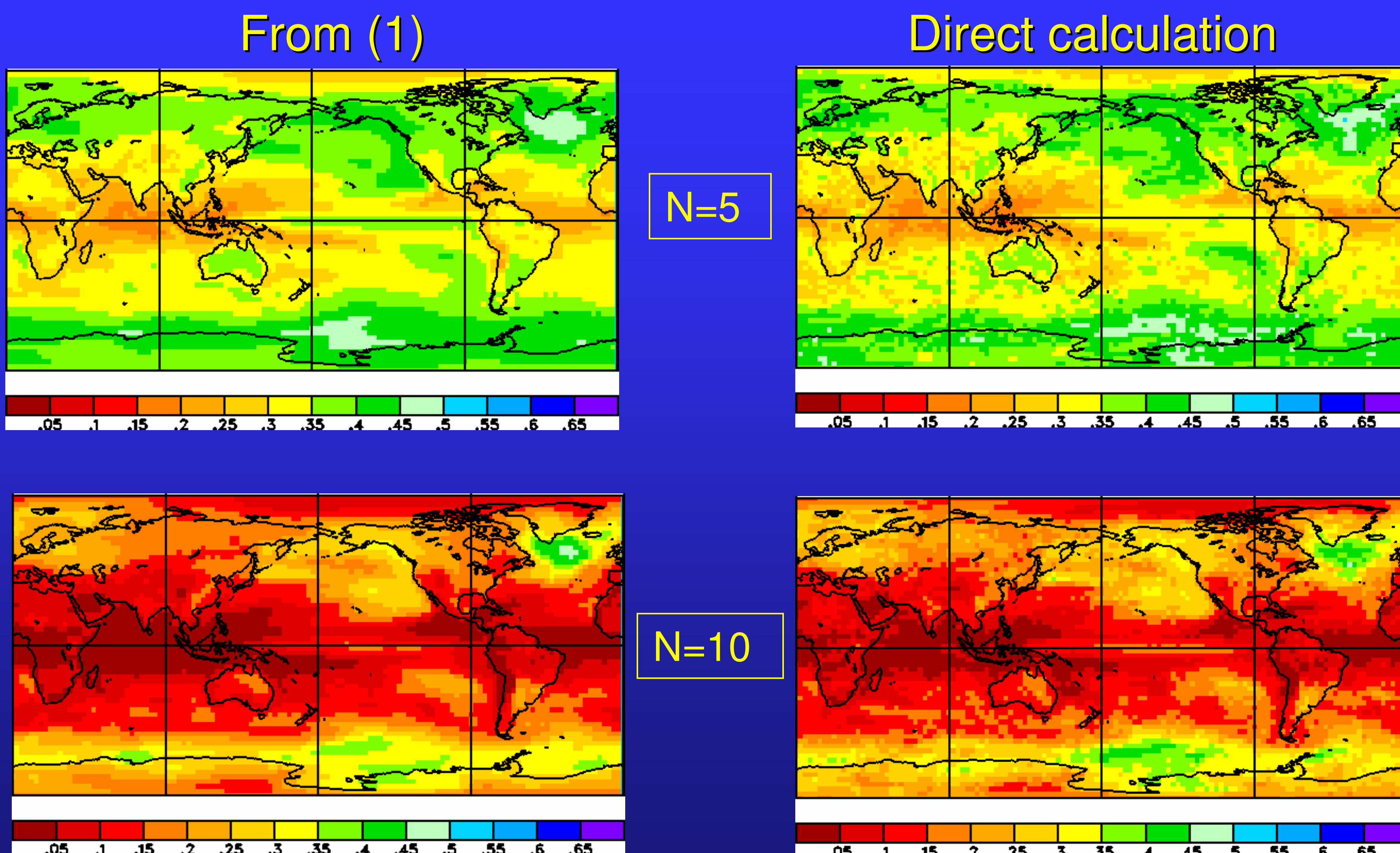


Multi-model P_N (A1B)



Application to global mean temperatures

- Apply same analysis to model annual global means:

	B1			A1B		
N	ΔT_N	σ_N	P_N	ΔT_N	σ_N	P_N
5	0.081	0.081	16.2%	0.128	0.084	4.8%
10	0.164	0.071	1.3%	0.261	0.084	0%

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10	0.164	0.071	1.3%	1.0%	0.084	0%	.09%

Conclusions

- Next-pentad/decade cooling
  - *most* likely in N Atl, Southern Ocean
    N Europe, NW North America
  - *least* likely in tropical Ind, Atl, Pac ITCZ
    Maritime Continent, W tropical S America
    & Africa, Arabian Peninsula
- *Global* cooling episode in present/future climate appears
  - "not too unlikely" for N=5 (P_N ~ 5-10%)
  - *exceptionally unlikely* for N=10 ($P_N \lesssim$ 1%)
- P_N can be estimated from $\overline{\Delta T}_N$, σ_N
- Statistics of successive differences vs N being explored with AR models

To do

- Examine whether results consistent between 2001-2050 and 2051-2100 (approximate linearity of trend OK?)
- Apply AR(1) analysis to global means, 2D fields
- Scalings for σ_N, P_N vs *a*, σ_ε
- Use conditional probabilities to enhance predictability, e.g. if the previous decade was anomalously warm (above trend), to what extent is P_N enhanced?

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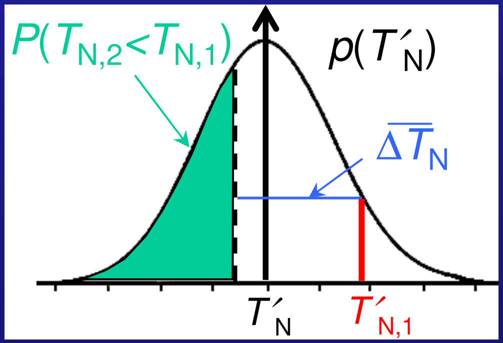
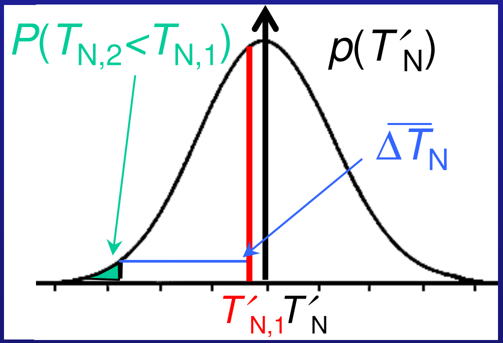
High $T'_{N,1} \rightarrow$ *high* prob that $T_{N,2} < T_{N,1}$



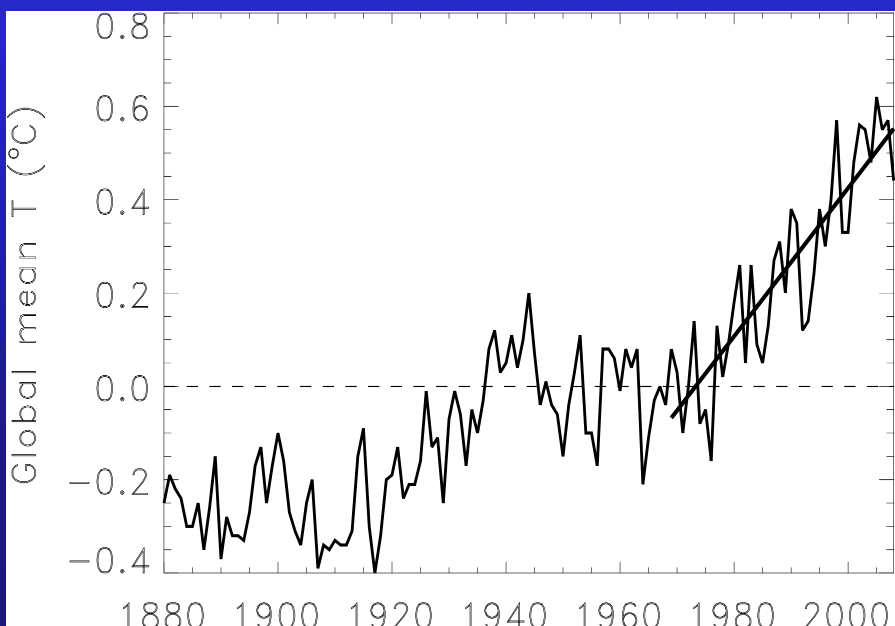
Lower $T'_{N,1} \rightarrow$ *low* prob that $T_{N,2} < T_{N,1}$



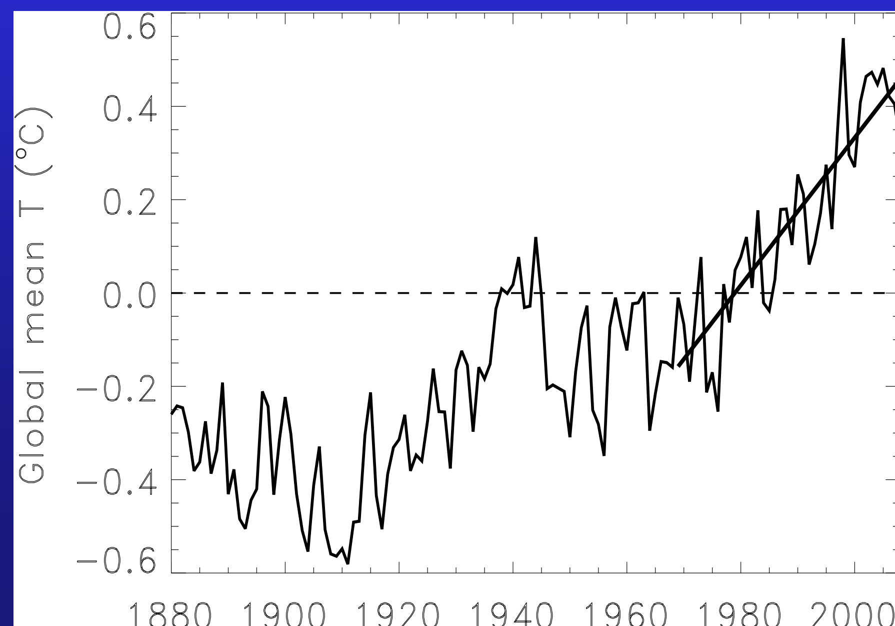
Observed global mean T

- Consider years 1969-2008
  - 8 pentads
  - 4 decades

GISS



HadCRUT3



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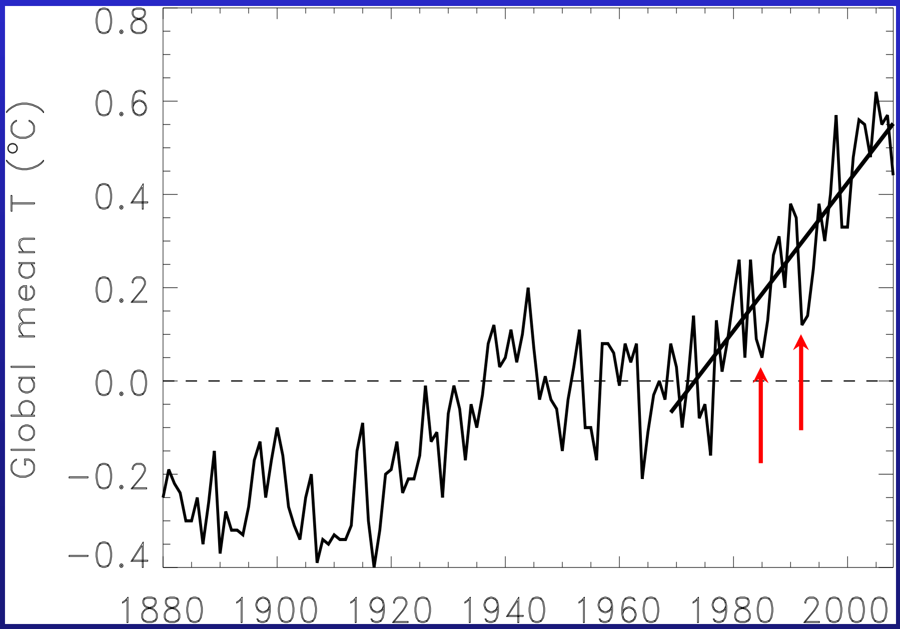

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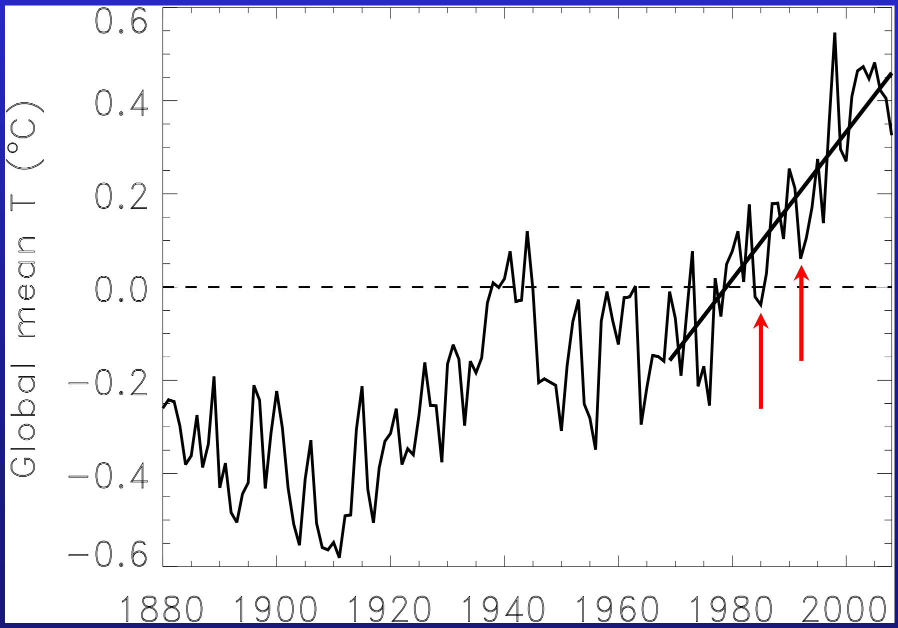

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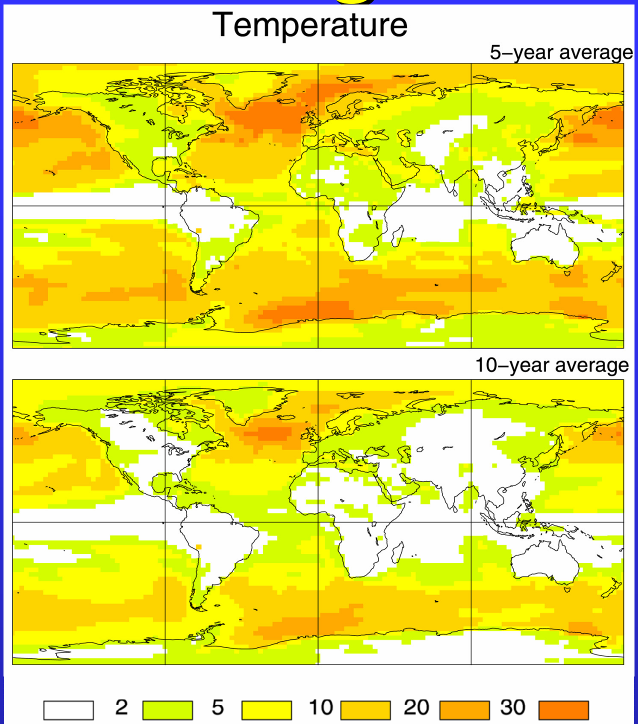
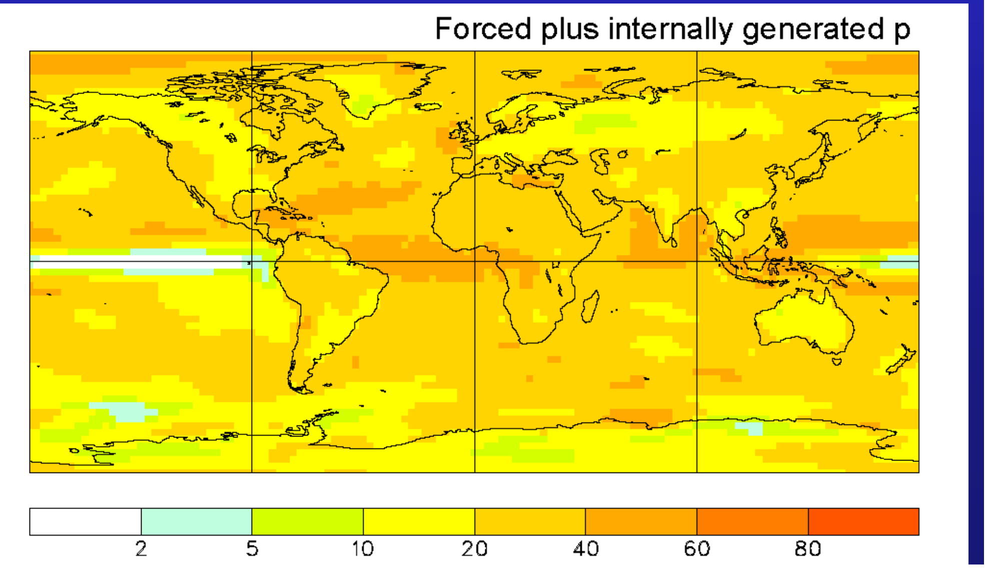
⇒ rate of warming similar to B1, but less variability (esp decadal)

Decadal predictability in a warming climate

- Boer & Lambert (GRL, 2008): "Traditional" predictability of N-year means (*potentially predictable variance fraction*) for control climate



- Boer (2009): Next-decade predictability (N=10) in presence of forced trend



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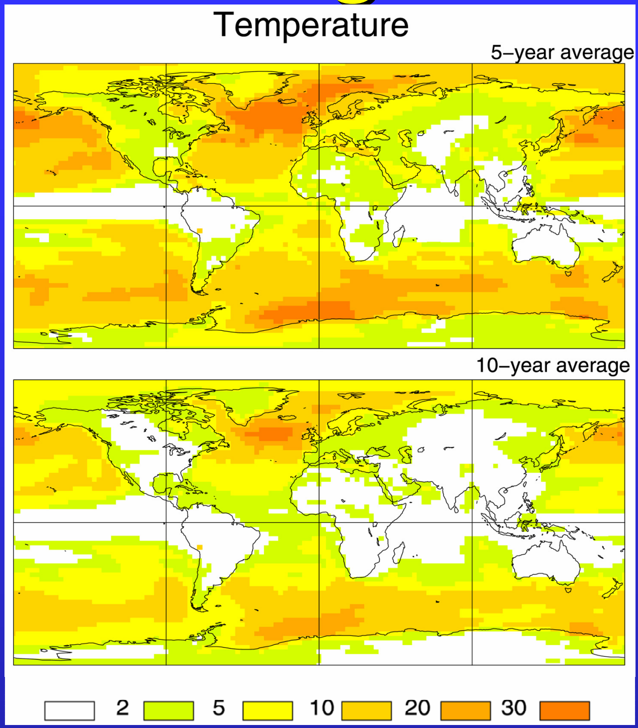

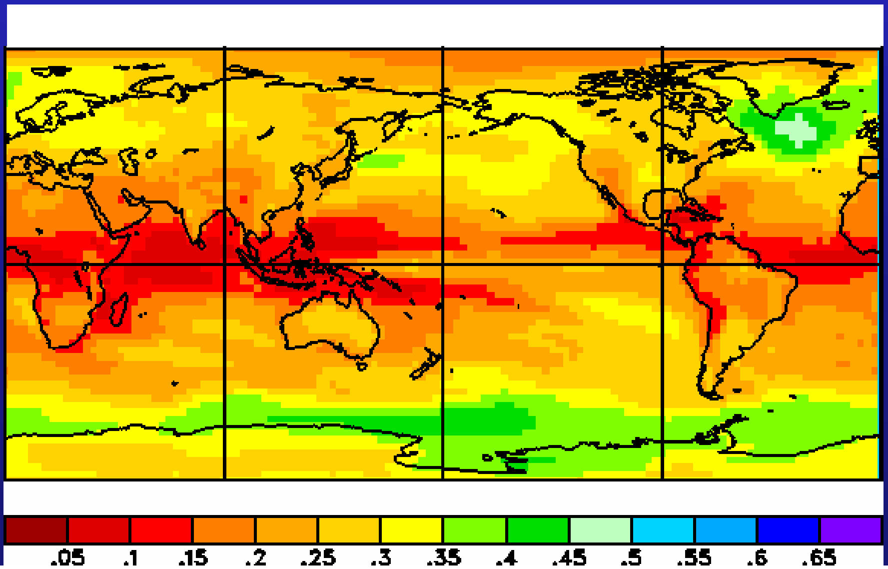

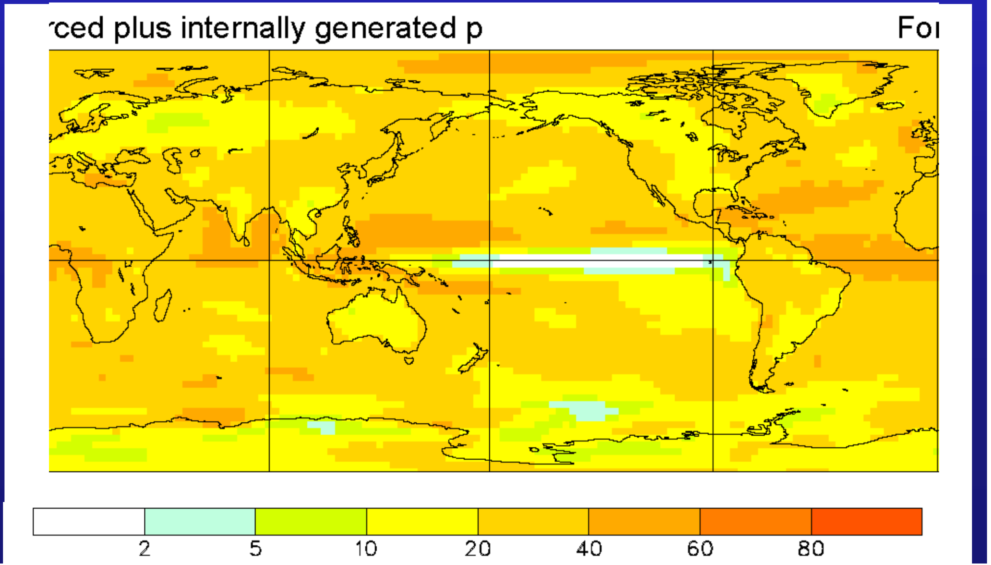

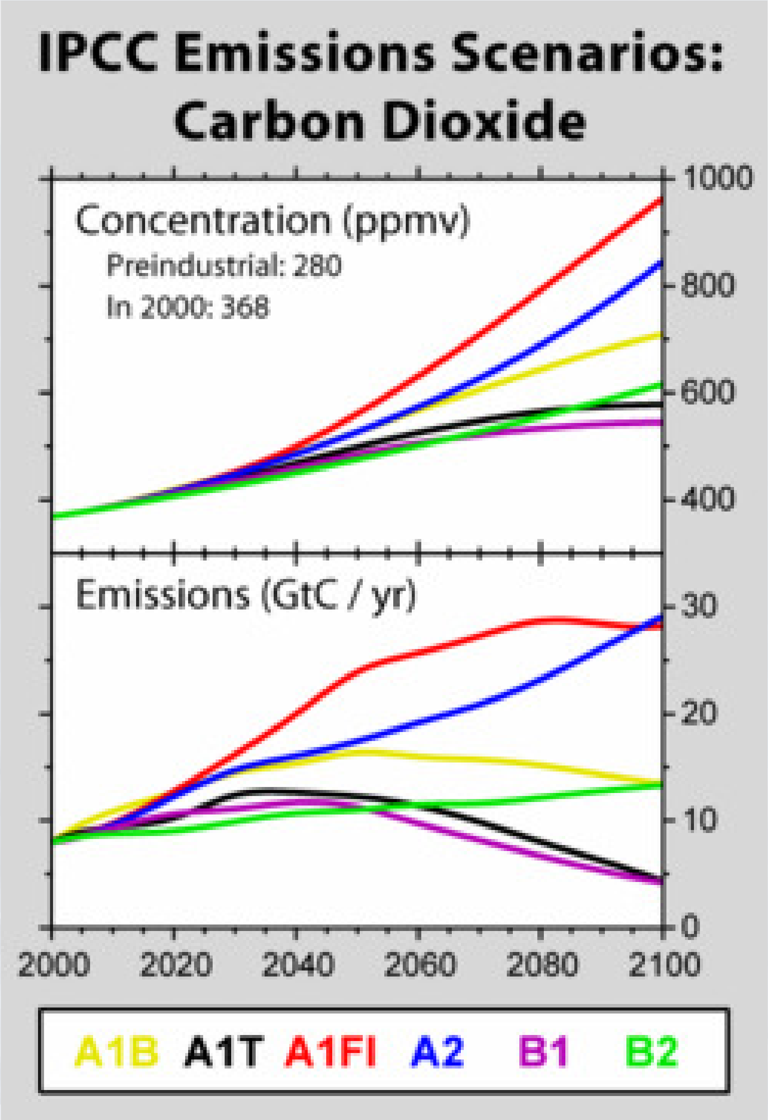

IPCC Emissions Scenarios:
Carbon Dioxide
Concentration (ppmv)
Preindustrial: 280
In 2000: 368
Emissions (GtC / yr)
1000
800
600
400
30
20
10
0
2000
2020
2040
2060
2080
2100
A1B
A1T
A1FI
A2
B1
B2