# Climate Monitoring and GPS Radio Occultation

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# The Reasons we Monitor Climate

- Is climate changing?
- Are humans responsible?
- Can we predict future climates?

Answers are

- Yes,
- Very likely,
- Not very well.

# Optimal fingerprinting

- Search for weak signals against a background of natural variability
- Associate cause and effect (“attribute” climate change)

$$\mathbf{d} = \sum_{i=1}^{m} \mathbf{s}_i \alpha_i + \mathbf{n}$$

- **d** is a mean-removed trend or change in the climate system
- The $\mathbf{s}_i$ are *m* signals predicted to exist in the data, computed by computations by global climate models
- **n** is a single realization of the interannual variability of the climate. It is only known in a statististical sense, with covariance **N** computed from long control runs of climate models.

# Optimal Fingerprinting Solution

$$\boldsymbol{\alpha} = \left( \mathbf{S}^T \mathbf{N}^{-1} \mathbf{S} \right)^{-1} \mathbf{S}^T \mathbf{N}^{-1} \mathbf{d}$$

$$\mathbf{A} = \left\langle \delta \boldsymbol{\alpha} \, \delta \boldsymbol{\alpha}^T \right\rangle = \left( \mathbf{S}^T \mathbf{N}^{-1} \mathbf{S} \right)^{-1}$$

Natural variability covariance matrix is not easily inverted, as in NWP applications. N.B.: N represents covariance in observed variables, not meteorological variables.

$$\mathbf{N} = \sum_{\mu} \mathbf{e}_{\mu} \lambda_{\mu} \mathbf{e}_{\mu}^T$$

$$\mathbf{N}^{-1} = \sum_{\mu} \mathbf{e}_{\mu} \lambda_{\mu}^{-1} \mathbf{e}_{\mu}^T$$

$$\mathbf{N} \mathbf{e}_{\mu} = \lambda_{\mu} \mathbf{e}_{\mu}$$

# The Truncation Problem

- Not all EOFs are good. With limited control runs to determine **N**, sampling error restricts ability to obtain reliable variances $\lambda_\mu$. The EOF series must be truncated.

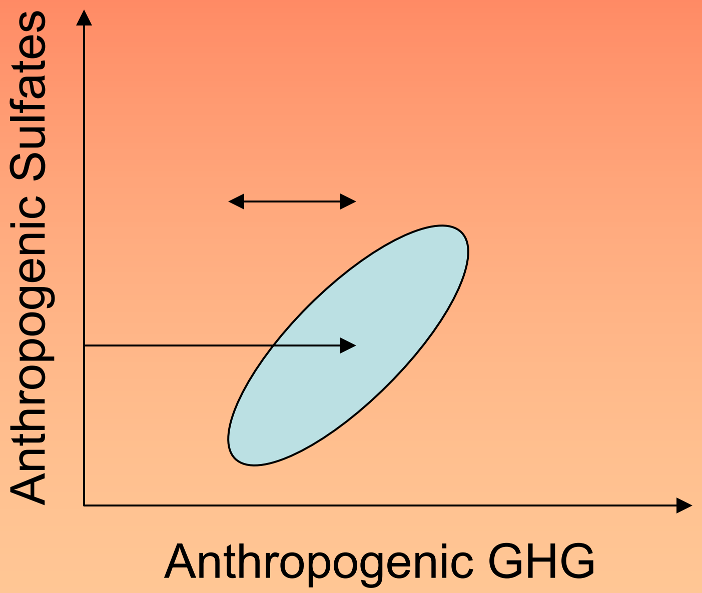
$$\tilde{\mathbf{N}} = \sum_{\mu=1}^{n} \mathbf{e}_\mu \lambda_\mu \mathbf{e}_\mu^T$$

$$\tilde{\mathbf{N}}^{-1} = \sum_{\mu=1}^{n} \mathbf{e}_\mu \lambda_\mu^{-1} \mathbf{e}_\mu^T$$

- Keep just *n* EOFs. How to determine *n*? With data use statistical f-test, e.g., keep residuals reasonable. Without data, subjective judgment is involved.

# Graphical Form for Solution

- Must determine signal-to-noise ratio (SNR) of detection. Gives probability with which a detected signal can be attributed to a specific cause rather than naturally occurring fluctuations of the climate.



*SNR* ~ 2.5

# Bayesian Implementation

- Relates prior information, data to posterior.

$$P(\boldsymbol{\alpha} \mid \mathbf{d}) \propto P(\mathbf{d} \mid \boldsymbol{\alpha})\, p(\boldsymbol{\alpha})$$

- $P(\mathbf{d}|\boldsymbol{\alpha})$ is the evidence function. Maximizing it is the essence of optimal fingerprinting ("linear multipattern regression").
- The prior reflects our best judgment about what should have happened with an associated uncertainty. Uncertainty in the prior is the same as precision of climate model predictive capability.

$$p(D \mid M) \propto \left|A_{\text{prior}}\right|^{-1/2} \exp\left[-\frac{1}{2}\chi^2\right]$$

$$\chi^2 = (\mathbf{d} - \mathbf{S}\boldsymbol{\alpha}_{mp})^T \tilde{\mathbf{N}}^{-1} (\mathbf{d} - \mathbf{S}\boldsymbol{\alpha}_{mp}) + (\boldsymbol{\alpha}_{mp} - \boldsymbol{\alpha}_p)^T \mathbf{A}_p^{-1} (\boldsymbol{\alpha}_{mp} - \boldsymbol{\alpha}_p)$$

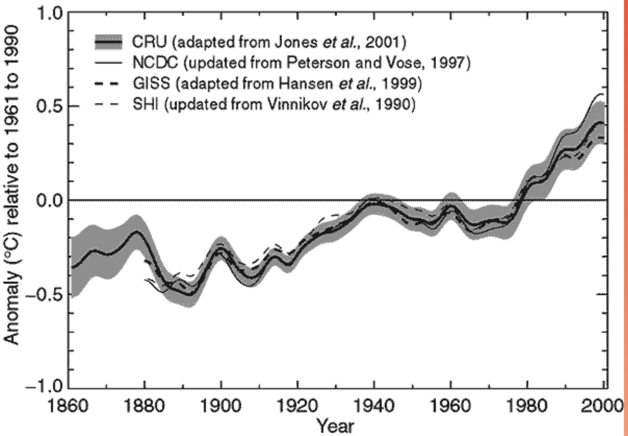
# Bayesian Message

- Proper implementation of prior: our cumulative uncertainty in predicting climate signals. Reflects all unknown/uncertain physics of the climate system.
- Can relate the question of attributability of human influence to capability of forecasting future climate
- Provides rigorous method of rating climate models according to their predictive capability. The best climate model is accurate and precise in its prediction.

See Leroy and North, *Terr. Atmos. Ocean.,* 2000.

# The Background of Climate Monitoring

- Evidence for global change
  - Surface air measurements
  - Natural proxy
- Satellites, particularly MSU
  - Not well calibrated
  - Do not cover the diurnal cycle

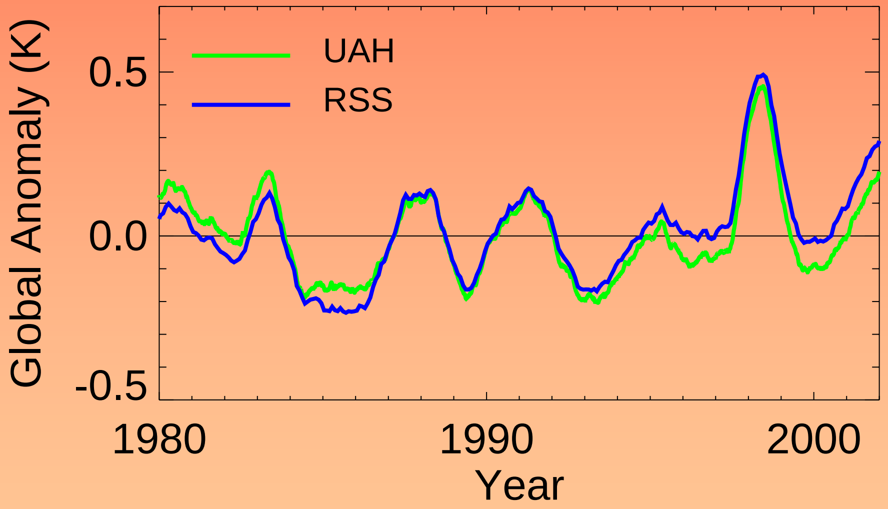


- Climate models differ widely in climate prediction
  - Overall sensitivity has 50% uncertainty
  - Regional trends show almost no agreement (T, precip)

We need to test climate models according to their predictive capability. Do trends in the climate system emerge as models predict?

# Climate Benchmarking

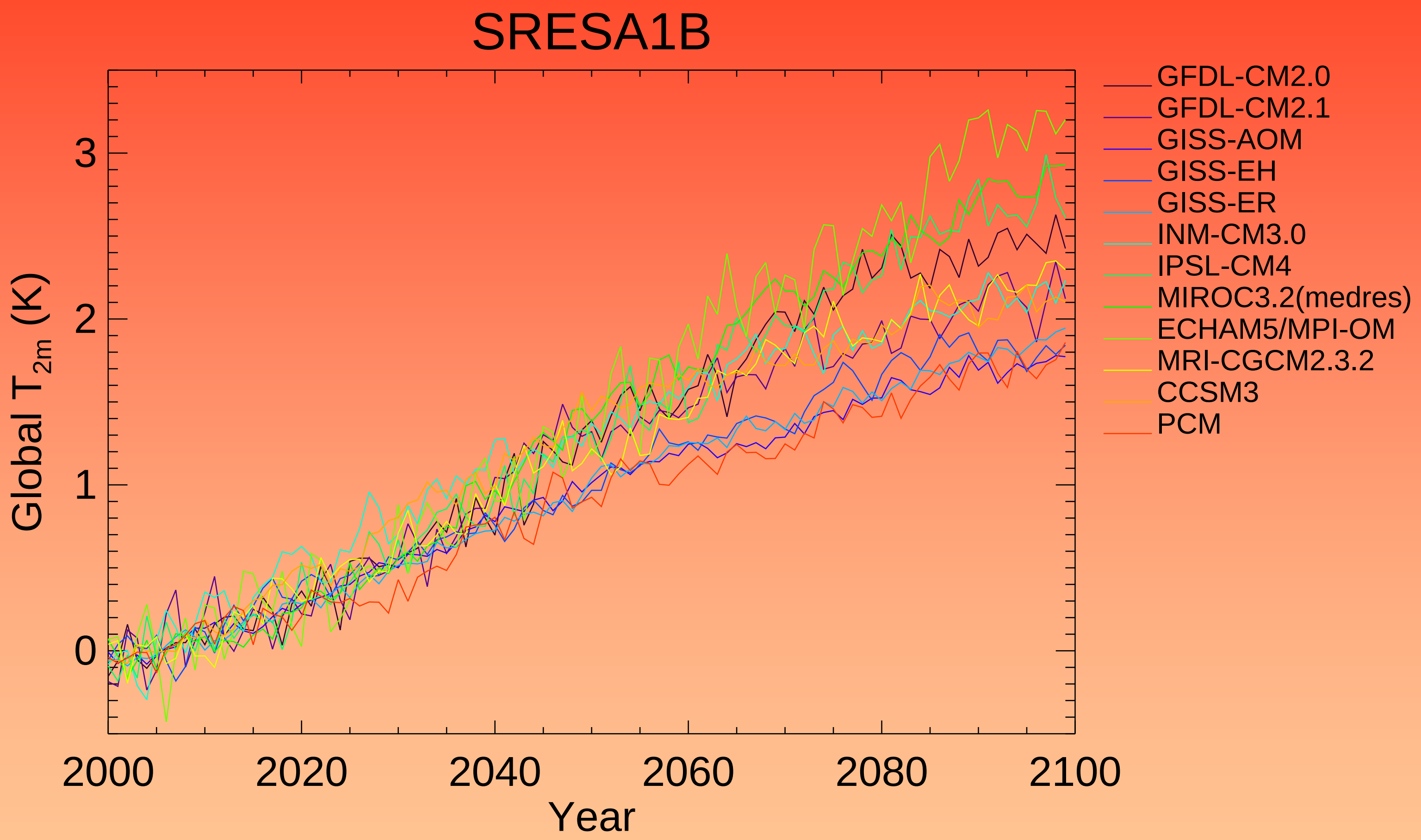
- Different attempts to analyze MSU data give different estimates of temperature trends in the troposphere.
- Need measurements which are unbiased, traceable to international standards, and therefore usable in perpetuity. GPS radio occultation fits this description, but requires specialized processing.



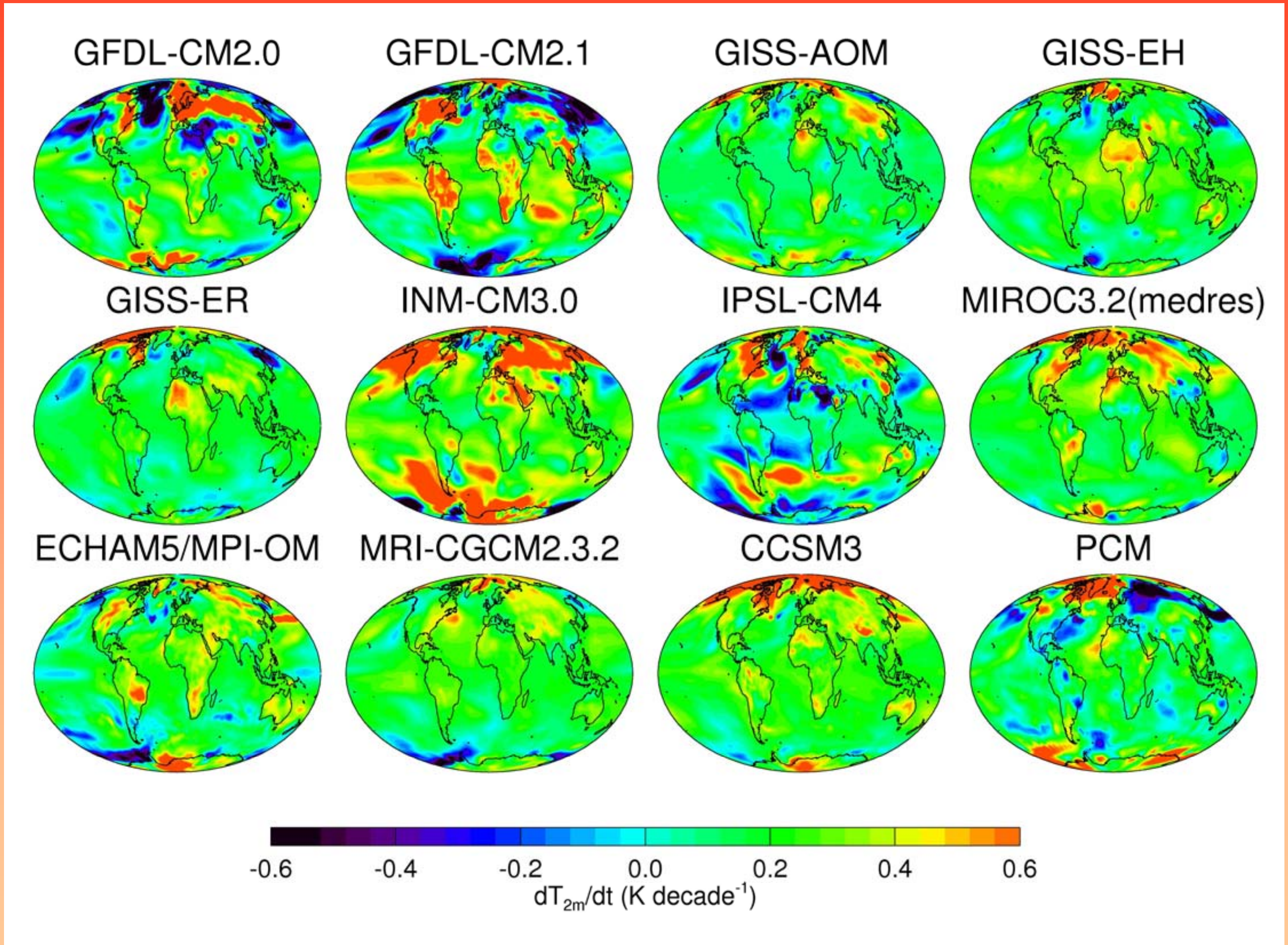
# Climate Model Evaluation Project (of IPCC 4AR)

- The Intergovernmental Panel for Climate Change (WMO, UN) is coordinative ***Climate Change 2007***, the Fourth Assessment Report (IPCC AR4) on the scientific basis for climate change
- For the chapters concerning model evaluation, the Climate Model Evaluation Project (CMEP) coordinated 21 climate modeling groups. Each submitted runs on simulation of pre-industrial climate, 20th century climate, present day climate, and scenarios of future climates.
- This ensemble of runs will allow us to assess what it will take to authoritatively find a human influence on climate and what to look for to determine the best models. We use the SRES A1B runs, a middle-of-the-road estimate of future trends in greenhouse gas emissions.

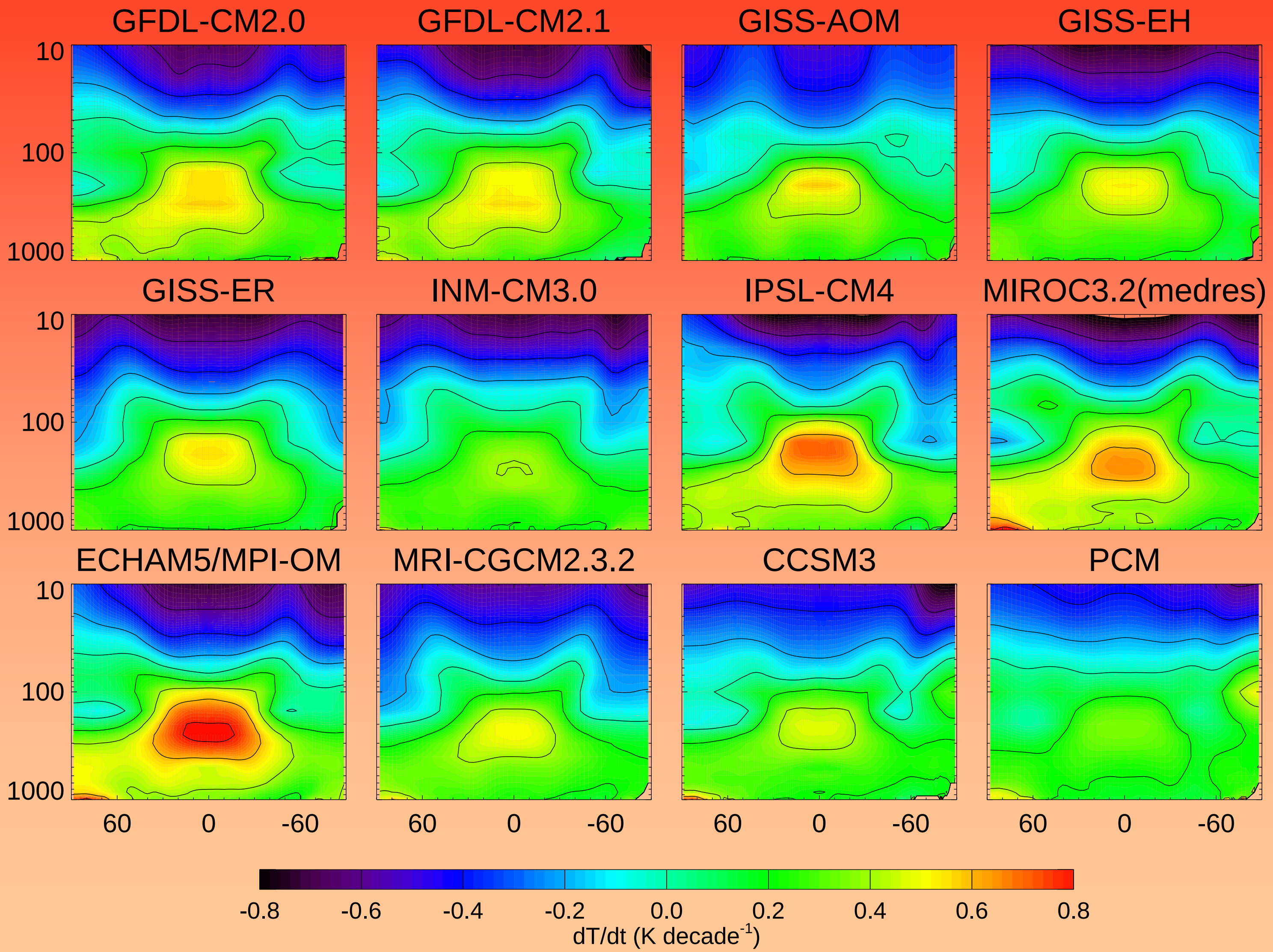
# SRES A1B Surface Air



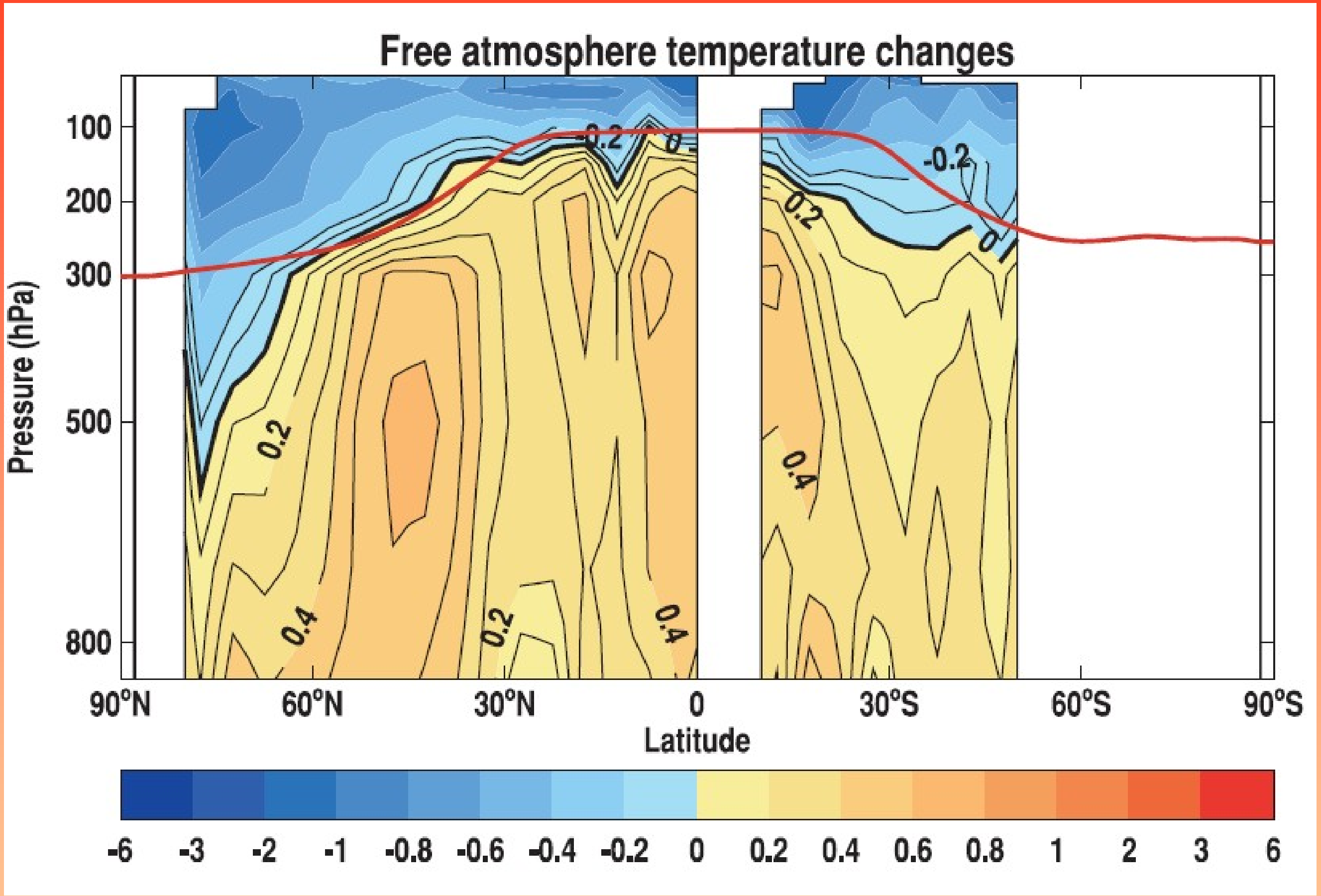
# SRES A1B Surface Air Patterns



# Zonal Average Temperature Trends

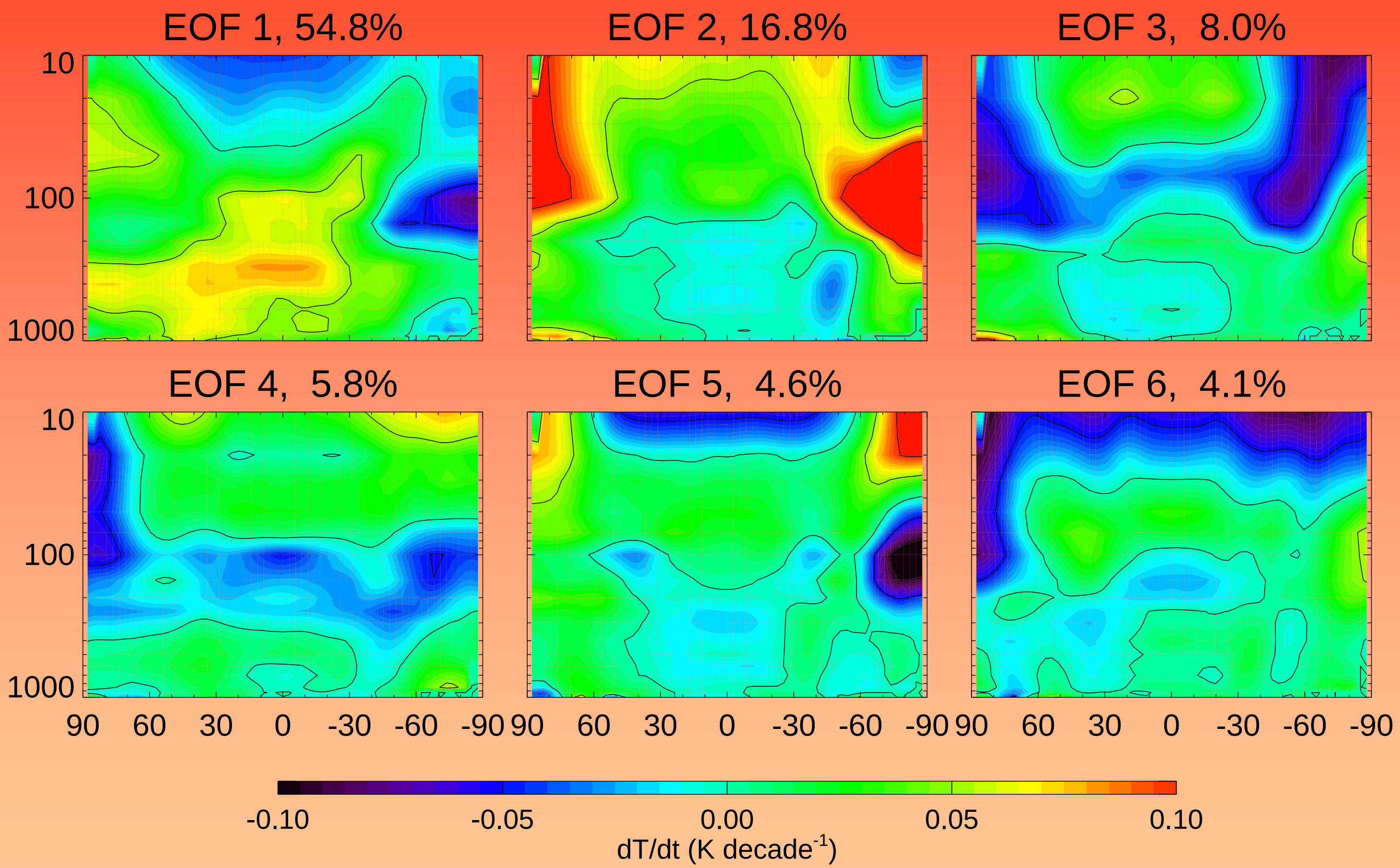


# What do Radiosondes Show?



Tett, S.F.B. et al., *J. Geophys. Res.*, **107**(D16), art. no. 4306, 2002.

# Upper Air Trend Uncertainty EOFs



# Upper Air Height Trends (Equations)

Geopotential height measures thermal expansion of the atmosphere beneath it.

Geopotential height can be obtained from radio occultation by integrating from the top of the atmosphere downward.

$$h(p) = h_s + \int_p^{p_s} \frac{RT(p)}{\bar{\mu} g_0} \, d \ln p$$

$$\frac{dh}{dt} = \frac{RT_s}{\bar{\mu} g_0} \frac{d \ln p_s}{dt} + \int_p^{p_s} \frac{R}{\bar{\mu} g_0} \left( \frac{dT}{dt} \right) d \ln p$$

# Geopotential Height from GPS RO

Geopotential height is geopotential energy per unit mass plus centrifugal potential with respect to the mean sea-level geoid. ***Absolutely, positively, without question must use a gravity model!***

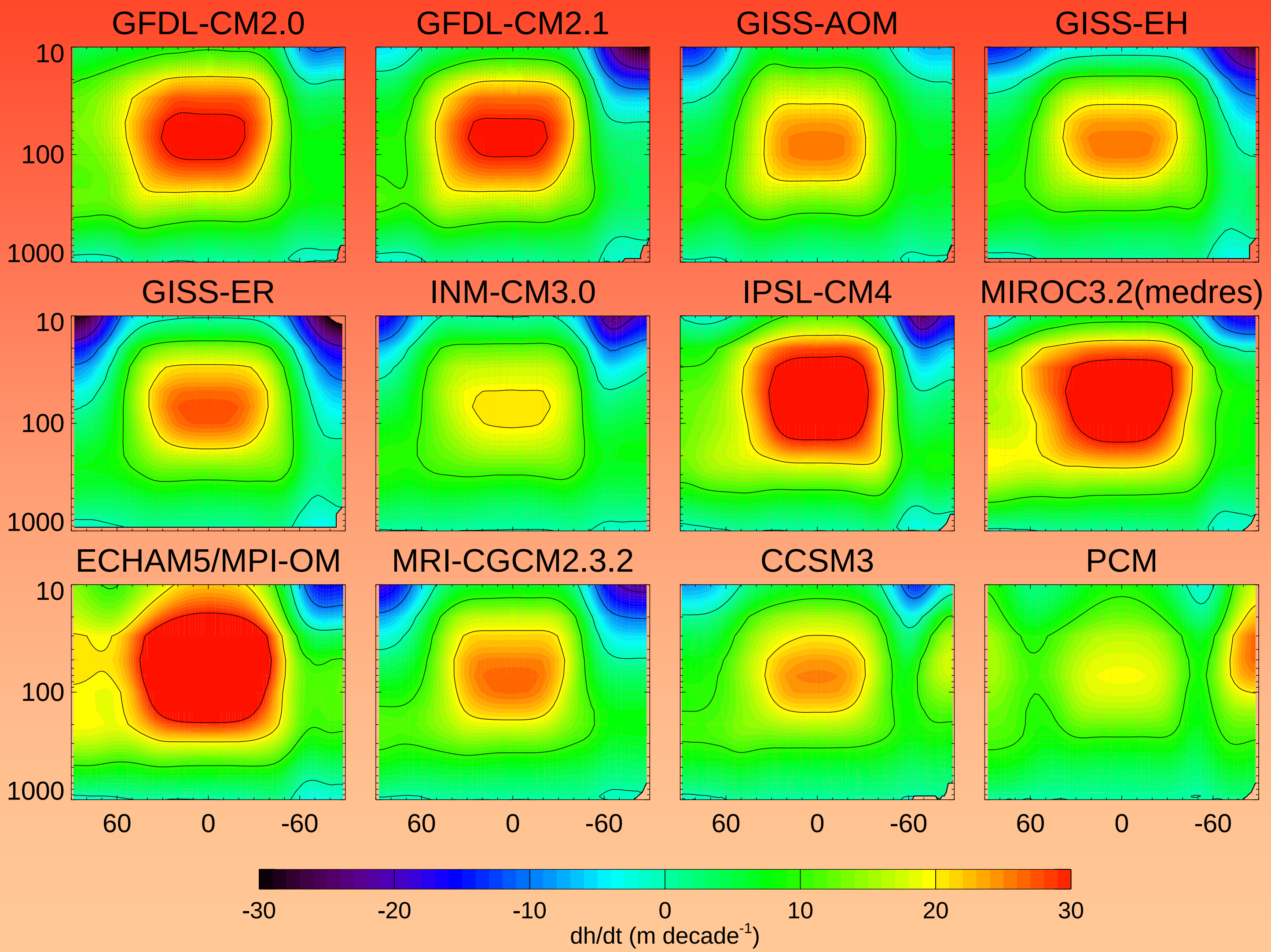
$$U(\mathbf{r}) = \frac{GM_e}{|\mathbf{r}|}\left[1 - \sum_{l=2}^{\infty}\left(\frac{R_e}{|\mathbf{r}|}\right)^l \sum_{m=-l}^{l} c_{l,m} Y_m^l(\sin\theta)\, e^{im\lambda}\right] - \frac{1}{2}\Omega^2 r_\perp^2$$

$$h(\mathbf{r}) = \frac{U(\mathbf{r}) - U_{msl}}{g_0}$$

Gravity model gives cl,m, necessary only to 300 km resolution.

$g_0$=9.80665 m s$^{-2}$

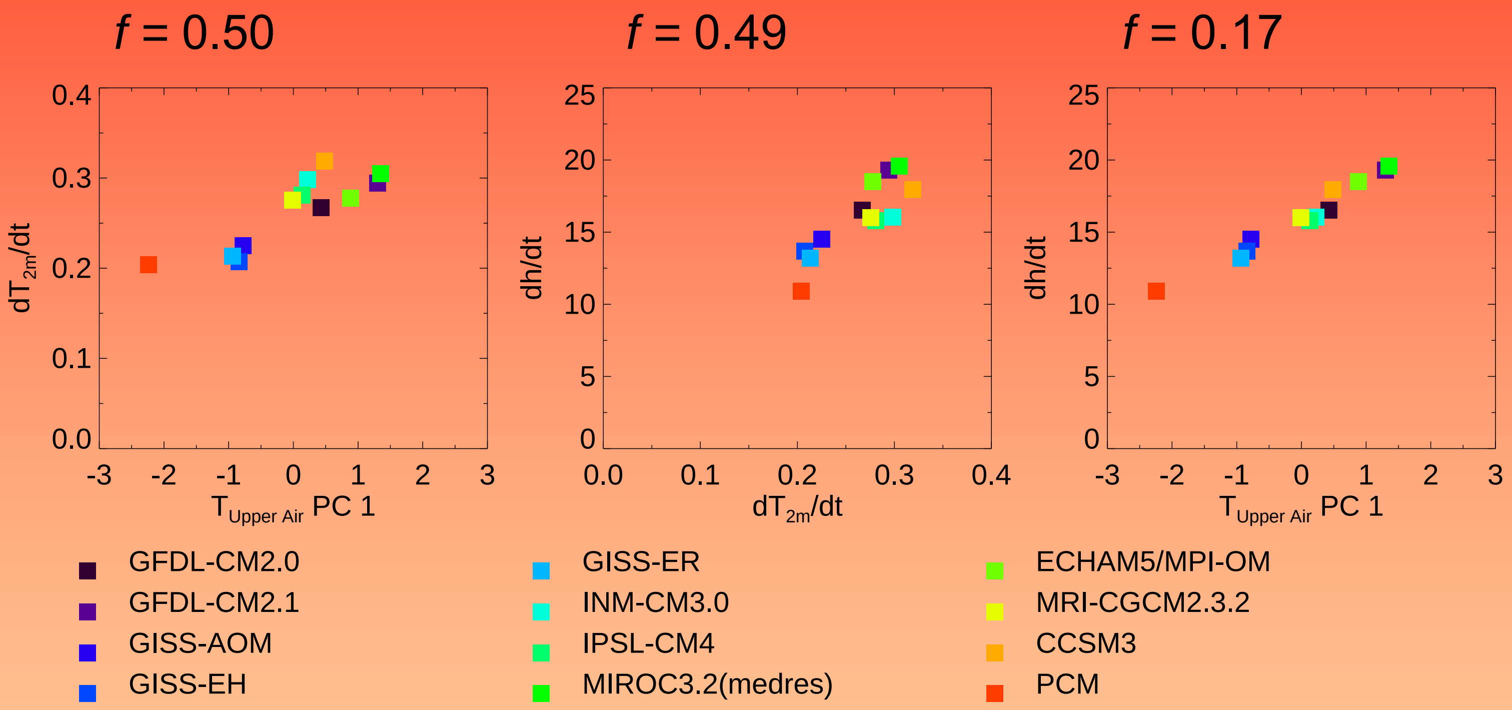
# Upper Air Height Trends (Plots)



# Comparing Indicators of Global Change

- Conventional way: global average surface air temperature $dT_{2m}/dt$
- More physical way: thickness of the troposphere $dh_{trop}/dt$
- Statistical way: principal component of zonal average temperature trends PCP EOF 1

# Comparing Indicators of Global Change



***Thermal expansion of the troposphere and EOF PC are far better measures of climate sensitivity than surface air temperature.***

# Trends in Microwave Refractivity

Empirical microwave refractivity:

$$N = (n-1)\times 10^{6} = (77.6\,\mathrm{K/hPa})\left(\frac{p}{T}\right) + (373\cdot 10^{3}\,\mathrm{K}^{2}/\mathrm{hPa})\left(\frac{p_W}{T^{2}}\right)$$

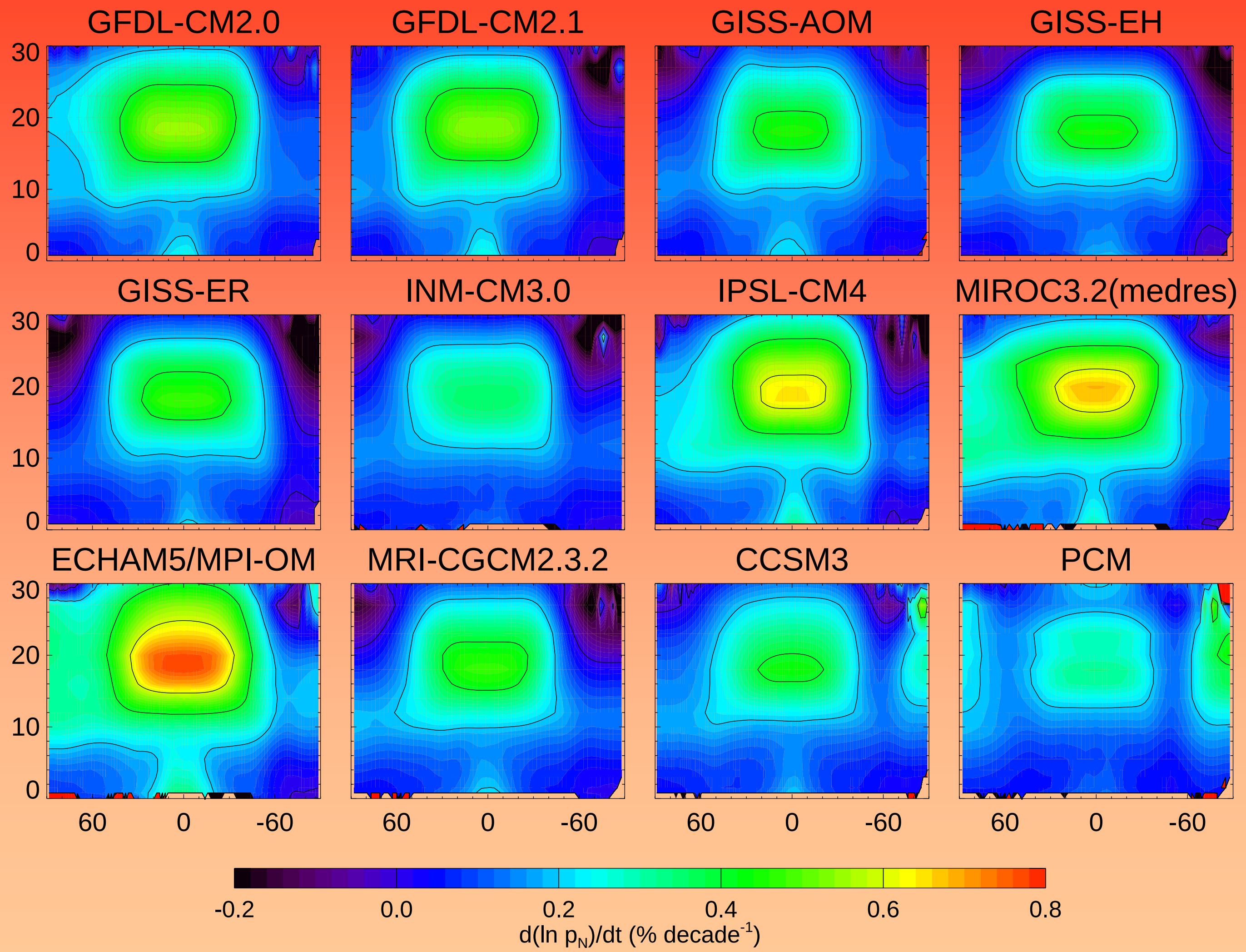
Dry pressure, computed from data, relationship to *p, T, q*:

$$p_N(h) \cong p(h) + 7725\,\mathrm{K}\int_0^{p(h)} \frac{q}{T}\,dp'$$

Relationship of dry pressure and thermal expansion:

$$\left.\frac{dh}{dt}\right|_p = H \left.\frac{d\ln p}{dt}\right|_h$$

# Trends in Dry Pressure



# Climate Signal Detection

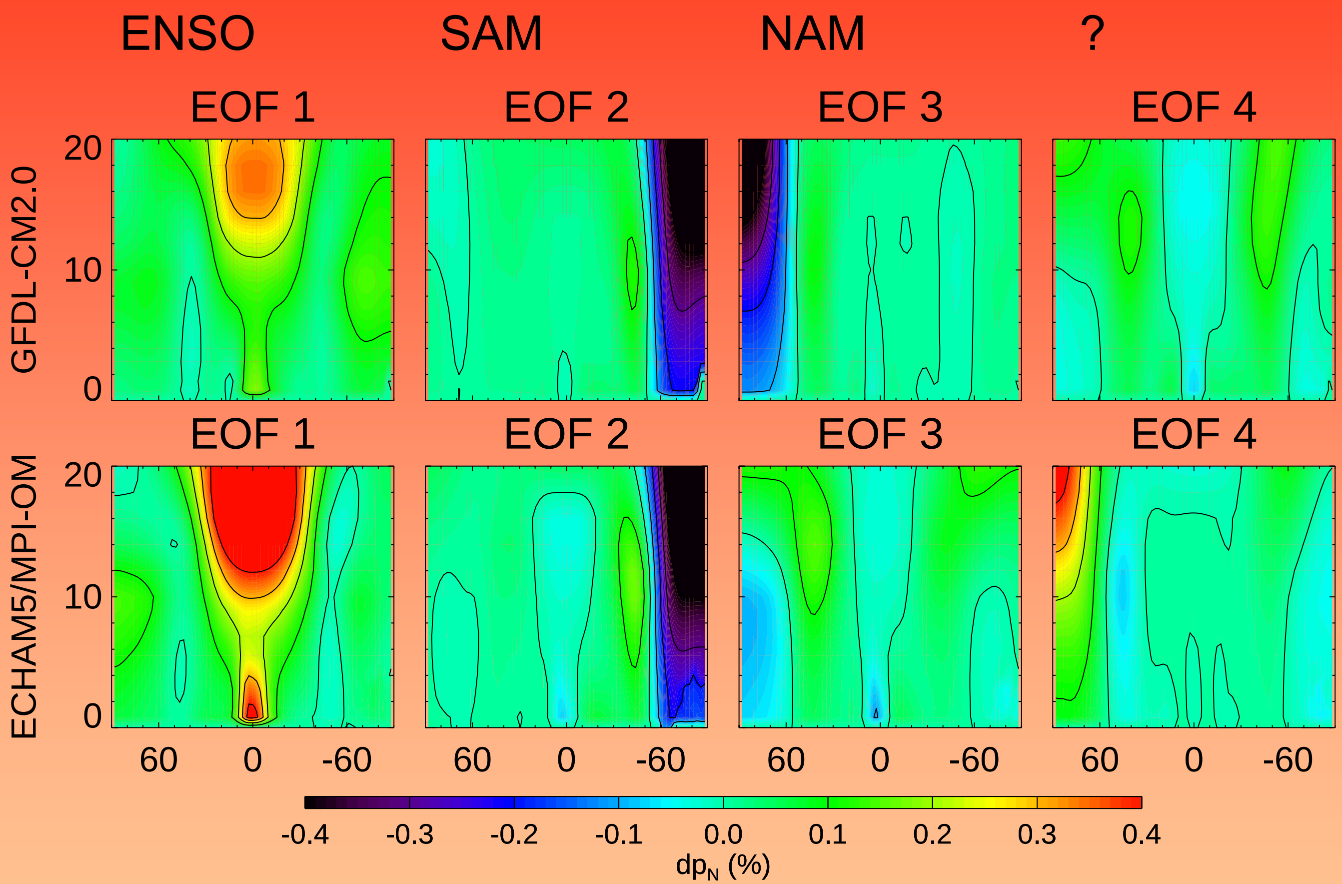
- How long does it take to reach 3-sigma (99% confidence)?
- What do we look for to optimize detection?

**Apply optimal fingerprinting.** Decompose noise by eigenvector (which accounts for correlations in the climate system), and preferentially weight toward those components with greater signal relative to the noise contributed by natural variability. The results are

- an estimate for the amount of time it takes for the signal to emerge above the natural variability, and
- the pattern which reveals the detection quickest.

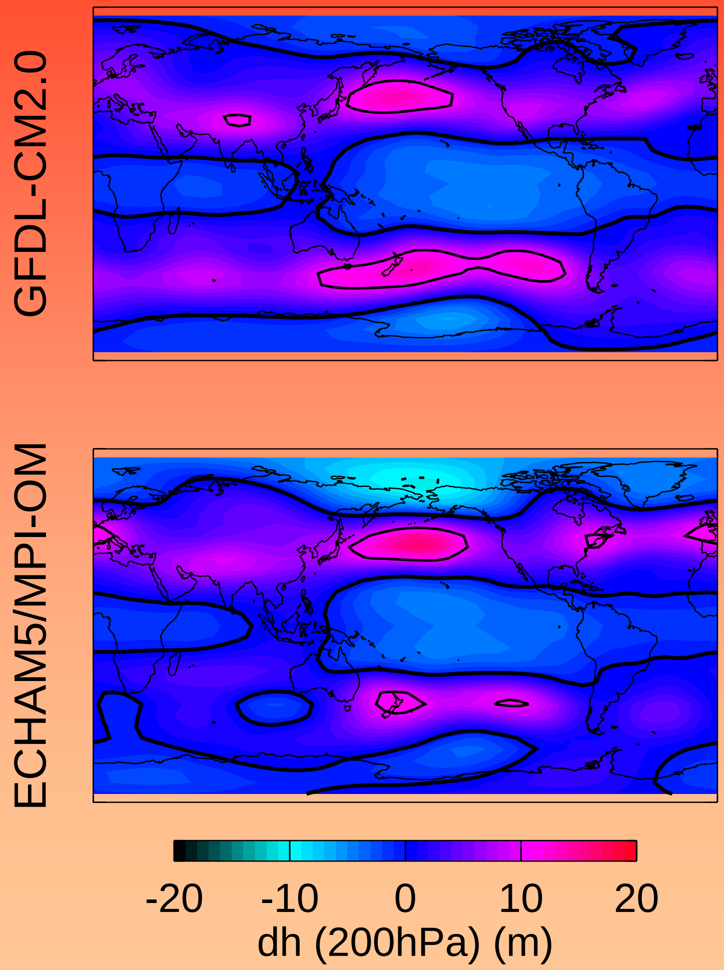
$$SNR = (\dot{\mathbf{s}}^{\mathrm{T}}\mathbf{N}^{-1}\dot{\mathbf{s}})^{1/2}\,\Delta t = \left[\sum_{\mu=1}^{m} \frac{\left\langle \mathbf{e}_{\mu}, \dot{\mathbf{s}} \right\rangle^{2}}{\lambda_{\mu}}\right]^{1/2} \Delta t$$

# EOFs of Dry Pressure Natural Variability



**Concepts:** ENSO, annular modes, geostrophic balance

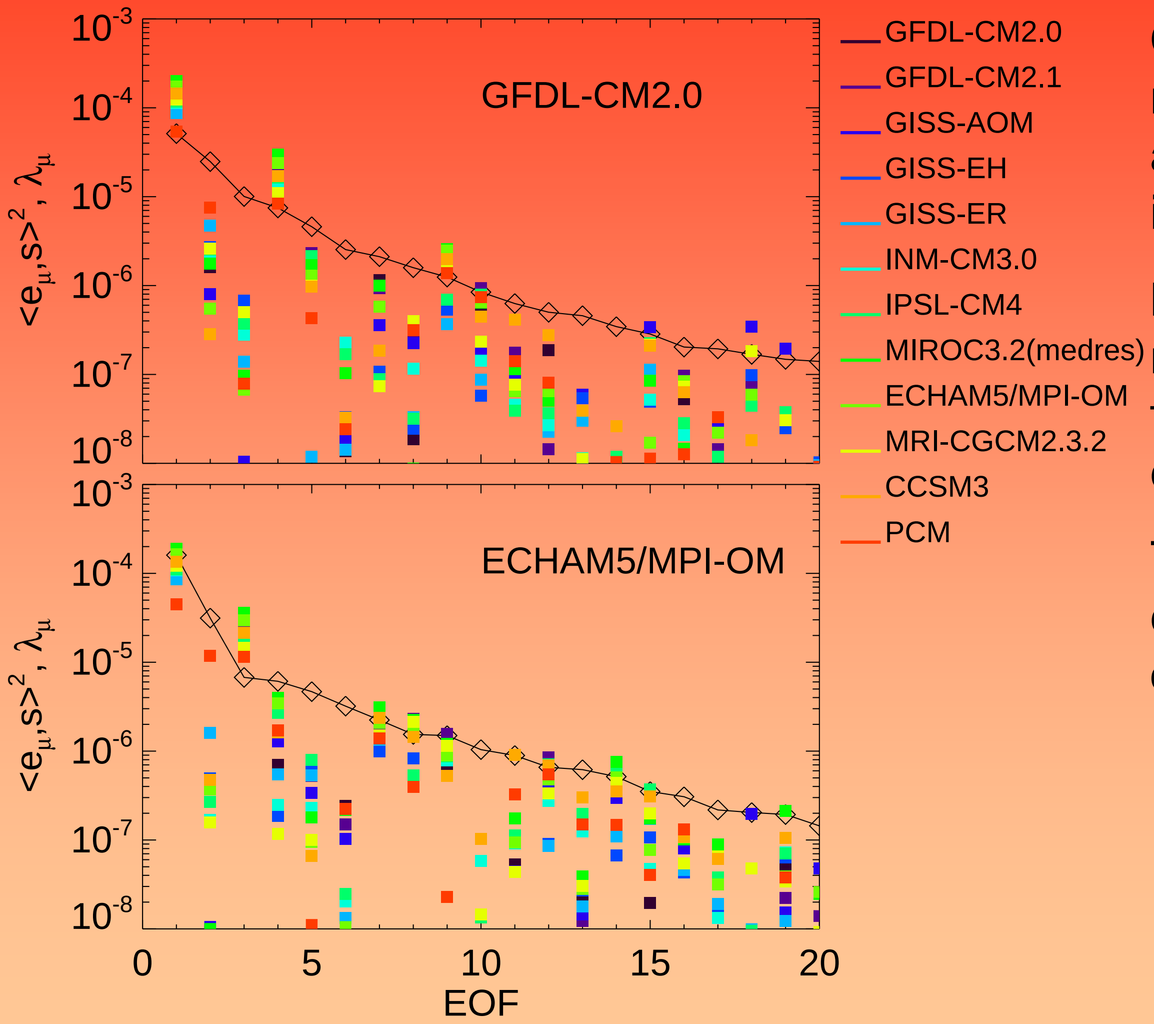
# The Mystery Mode



**Lorenz & Hartmann (2001 & 2003)** found these modes in the northern and southern hemispheres but did not notice they are coupled.

The **Jet Migration Mode**.

# Projection & Eigenvalue Spectra

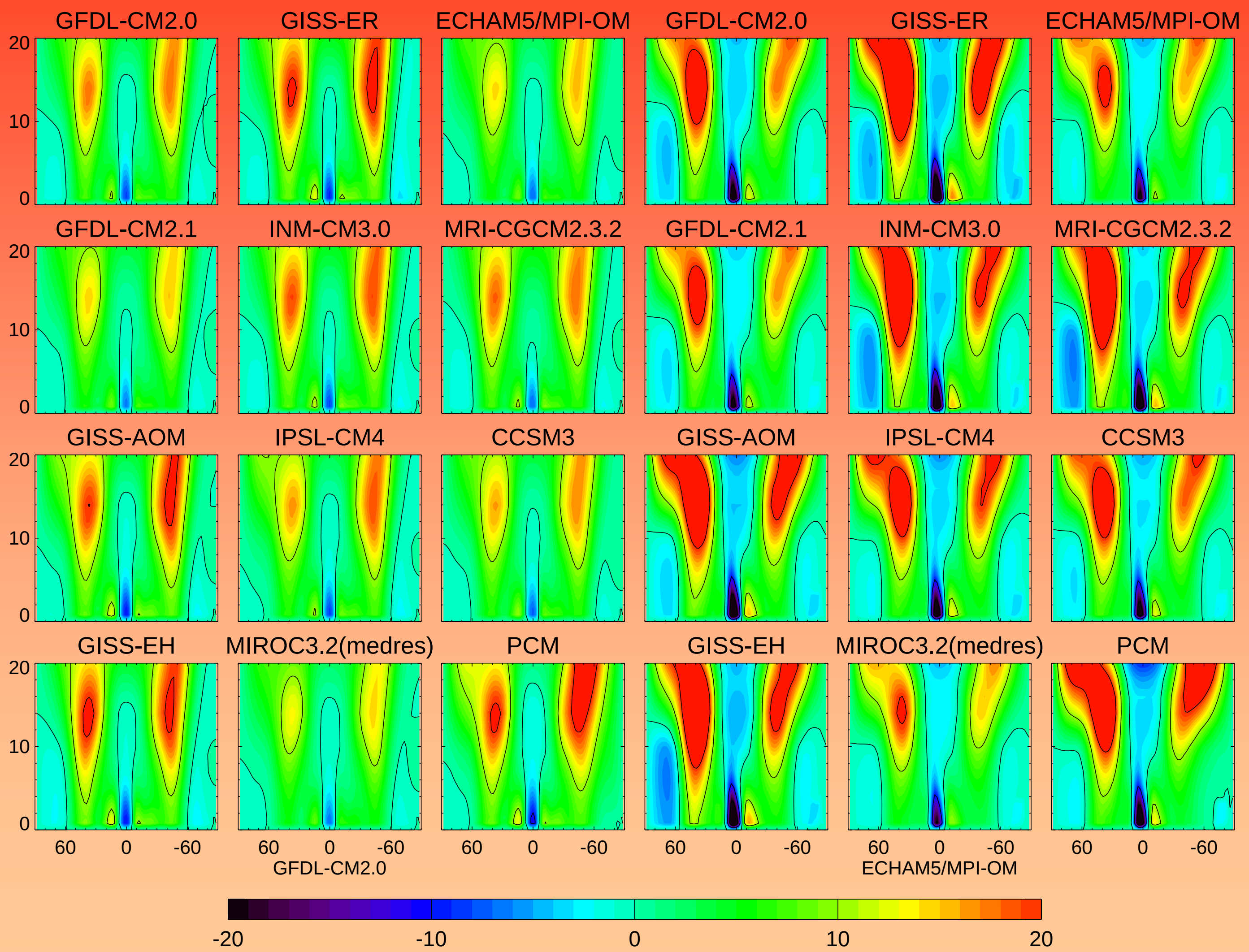


**Clustering** of points means model agreement on human influence.

**Dispersion** means model uncertainty in forecasting climate change.

The Jet Migration Mode contributes most to optimal detection.

# Fingerprints



# 3-Sigma Detection Times (GFDL, ECHAM)

| Model | Time (yrs) |
|---|---|
| GFDL-CM2.0 | 13.01 |
| GFDL-CM2.1 | 11.82 |
| GISS-AOM | 15.79 |
| GISS-EH | 15.61 |
| GISS-ER | 16.33 |
| INM-CM3.0 | 14.97 |
| IPSL-CM4 | 13.93 |
| MIROC-3.2(medres) | 10.64 |
| ECHAM5/MPI-OM | 11.67 |
| MRI-CGCM2.3.2 | 14.92 |
| CCSM3 | 13.30 |
| PCM | 19.03 |

| Model | Time (yrs) |
|---|---|
| GFDL-CM2.0 | 13.57 |
| GFDL-CM2.1 | 12.97 |
| GISS-AOM | 17.31 |
| GISS-EH | 17.61 |
| GISS-ER | 19.05 |
| INM-CM3.0 | 16.85 |
| IPSL-CM4 | 15.03 |
| MIROC-3.2(medres) | 11.21 |
| ECHAM5/MPI-OM | 12.23 |
| MRI-CGCM2.3.2 | 17.55 |
| CCSM3 | 14.43 |
| PCM | 18.48 |

# Summary & Conclusions

- **Optimal fingerprinting** is used to attribute climate change to specific causes. Its **Bayesian implementation** shows that it is a component of climate model testing using trend data. The best climate model predicts climate change both accurately and precisely.
- **Thermal expansion** of the troposphere is a far superior indicator of global change than is global average surface air temperature.
- GPS radio occultation can detect bulk atmospheric change at the 3-sigma level (99% confidence) in **10 to 20 years**.
- The optimal filter for measuring global change demands tracking symmetric poleward drift of the mid-latitude jet.
- It is well worth looking at GPS/MET (1995) and CHAMP (2001-present) data to find global change. **Requires benchmark/SI-traceable processing.**

# Acknowledgments

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