Testing Climate Models with GNSS Radio Occultation

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Talk Outline

- Climate OSSE
  - Optimal Methods/Multi-pattern regression
  - Response: GPS Radio Occultation (RO)
- An Approach to Accuracy Requirements
- Discussion

Climate OSSE: The Science of a Benchmark

Benchmark Measurement

- Traceable to international standards
- Minimize sampling error

Climate OSSE

- Simulate trends in observable as produced by different models
- Explore information content with various contravariant fingerprints

Climate Uncertainty

- Shortwave forcing
- Longwave forcing
- Climate feedbacks & sensitivity

Climate OSSE Results

- Detection time and accuracy requirements
- How measurement constrains climate predictability
- Relative redundancy with other benchmark data types

Optimal Fingerprinting/Multi-pattern Regression

We are limited by the naturally occurring inter-annual variability of the climate system…so optimize.

Find signal amplitudes ($\boldsymbol{\alpha}_m$) and uncertainty ($\boldsymbol{\Sigma}_\alpha$) in a data set ($\mathbf{d}$) according to the signals' patterns ($\mathbf{s}_i$) against a background of natural variability, the eigenvectors and eigenvalues of which are $\mathbf{e}_\mu$ and λ_μ.

$$\frac{d\boldsymbol{\alpha}}{dt} = \mathbf{G}^{-1}\mathbf{H}\frac{d\mathbf{d}}{dt}$$

$$\mathbf{h}_i = \sum_{\mu=1}^{k} \lambda_\mu^{-1} \left\langle \mathbf{e}_\mu, \mathbf{s}_i \right\rangle \mathbf{e}_\mu$$

$$\boldsymbol{\Sigma}_{d\boldsymbol{\alpha}/dt} = \mathbf{G}^{-1}$$

$$G_{i,j} = \left\langle \mathbf{h}_i, \mathbf{s}_j \right\rangle$$

GPS Radio Occultation

- Refractivity

$$N = (n-1)\times 10^6 = (77.6\,\mathrm{K\,hPa^{-1}})\frac{p}{T} + (363\times 10^3\,\mathrm{K}^2\,\mathrm{hPa^{-1}})\frac{p_\mathrm{w}}{T^2}$$

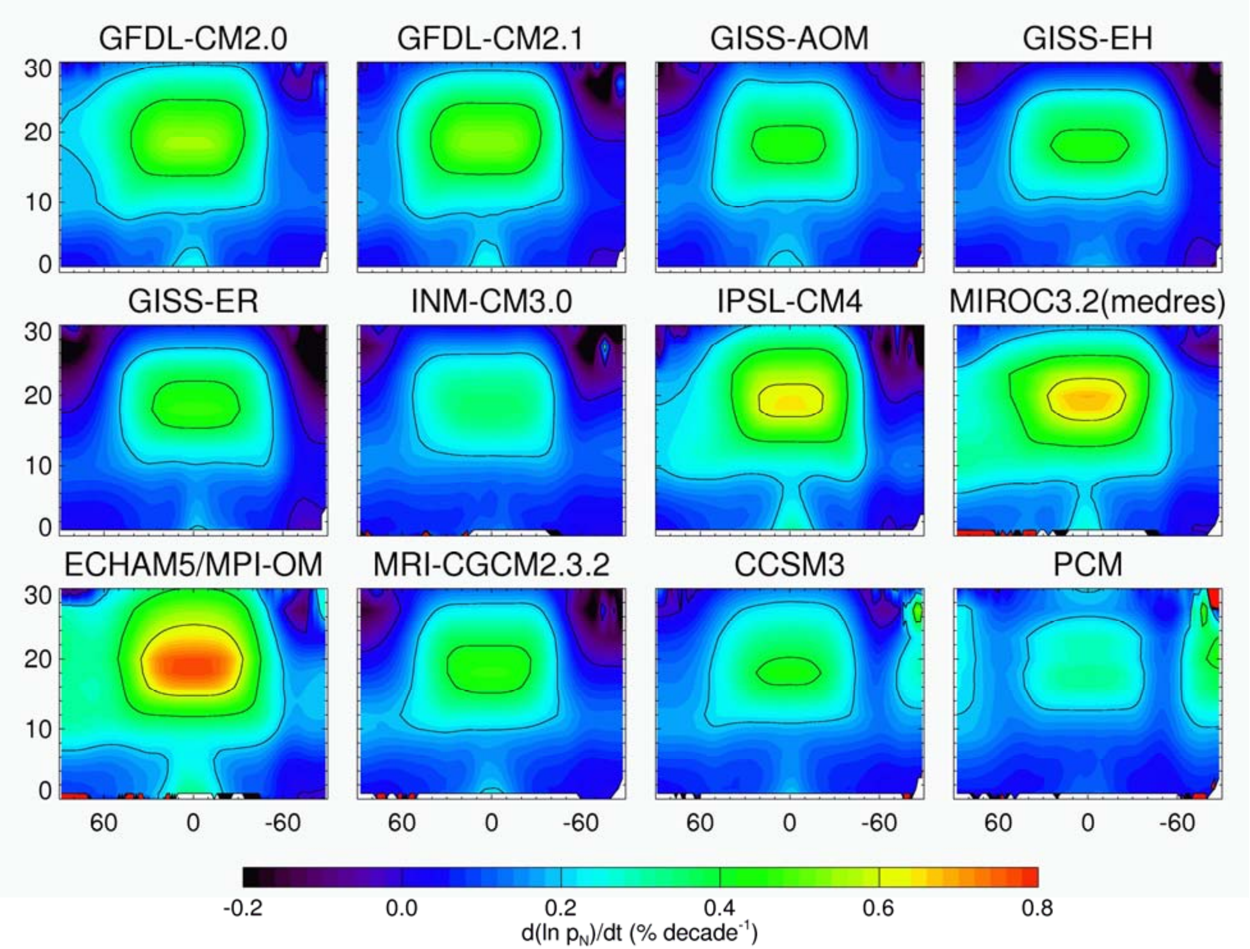
- "Dry" pressure

$$p_d(h) = (4.402\times 10^{-4}\,\mathrm{hPa\ m^{-1}})\int_h^\infty N\,dh \cong p(h) + (7521\,\mathrm{K})\int_0^{p(h)} \frac{q\,dp}{T}$$

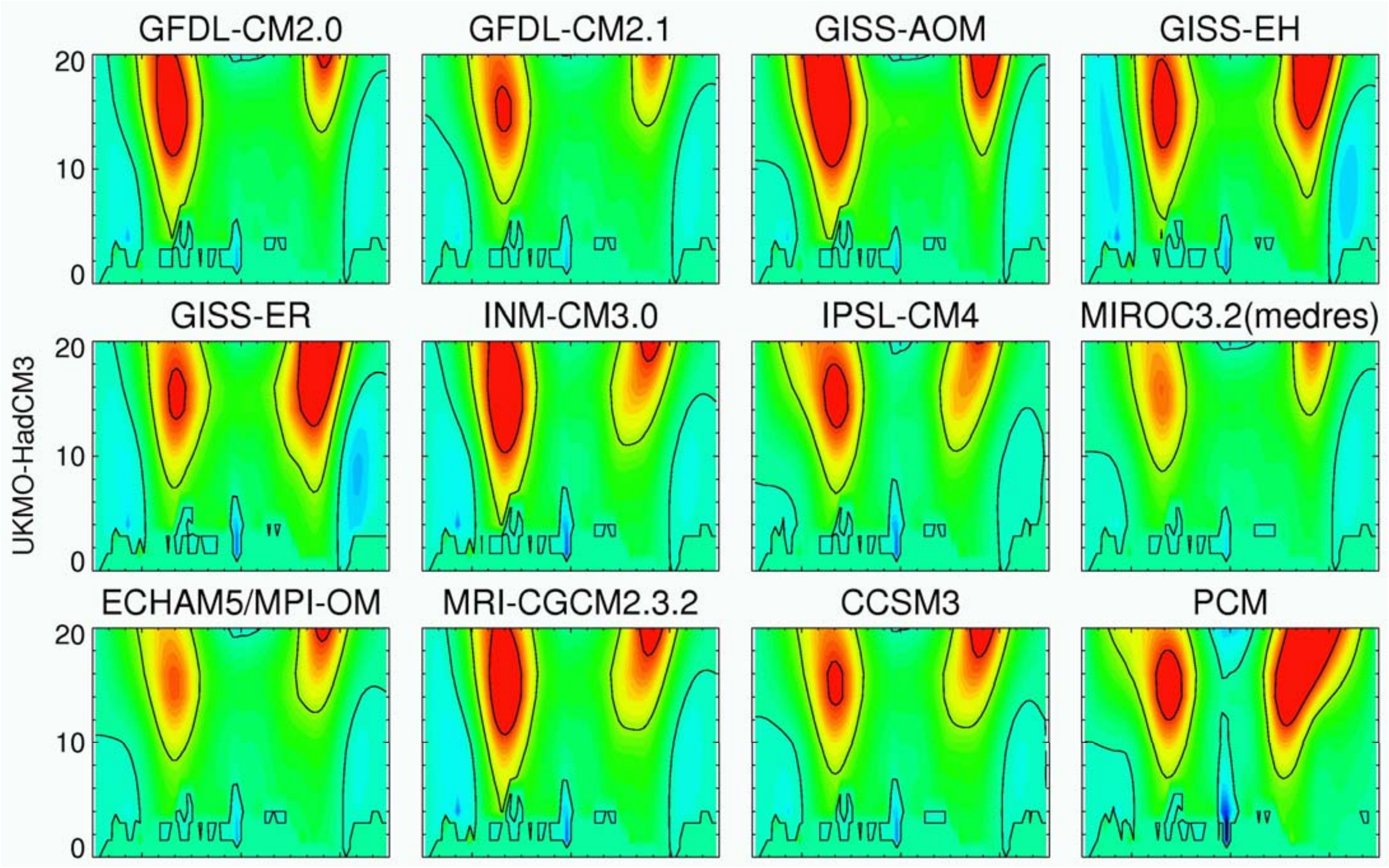
- Geopotential height

$$h = \left[(\Phi(\mathbf{r}) - \frac{1}{2}\Omega^2 r_s^2) - (\Phi - \frac{1}{2}\Omega^2 r_s^2)_\mathrm{msl}\right]/\,g_0$$

GPS RO Dry Pressure Tendency



Fingerprints



95% Detection Times

Model	**GFDL CM2.0** (yrs)	**ECHAM5/MPI-OM** (yrs)	**UKMO-HadCM3** (yrs)	**MIROC3.2 (medres)** (yrs)	**Tropospheric Expansion** (m $decade^{-1}$)
GFDL-CM2.0	8.67	9.05	8.29	6.63	11.02
GFDL-CM2.1	7.88	8.65	7.57	6.21	12.86
GISS-AOM	10.53	11.54	10.47	8.38	9.67
GISS-EH	10.41	11.74	10.77	8.50	9.12
GISS-ER	10.89	12.70	11.07	9.32	8.79
INM-CM3.0	9.98	11.23	9.79	8.15	10.71
IPSL-CM4	9.29	10.02	8.95	7.36	10.54
MIROC 3.2(medres)	7.09	7.47	6.83	5.39	13.04
ECHAM5/MPI-OM	7.78	8.16	7.45	5.87	12.34
MRI-CGCM2.3.2	9.95	11.70	9.92	8.35	10.68
CCSM3	8.87	9.62	8.68	6.80	11.97
PCM	12.69	12.32	11.95	8.45	7.27

Accuracy Requirements, Detection Times

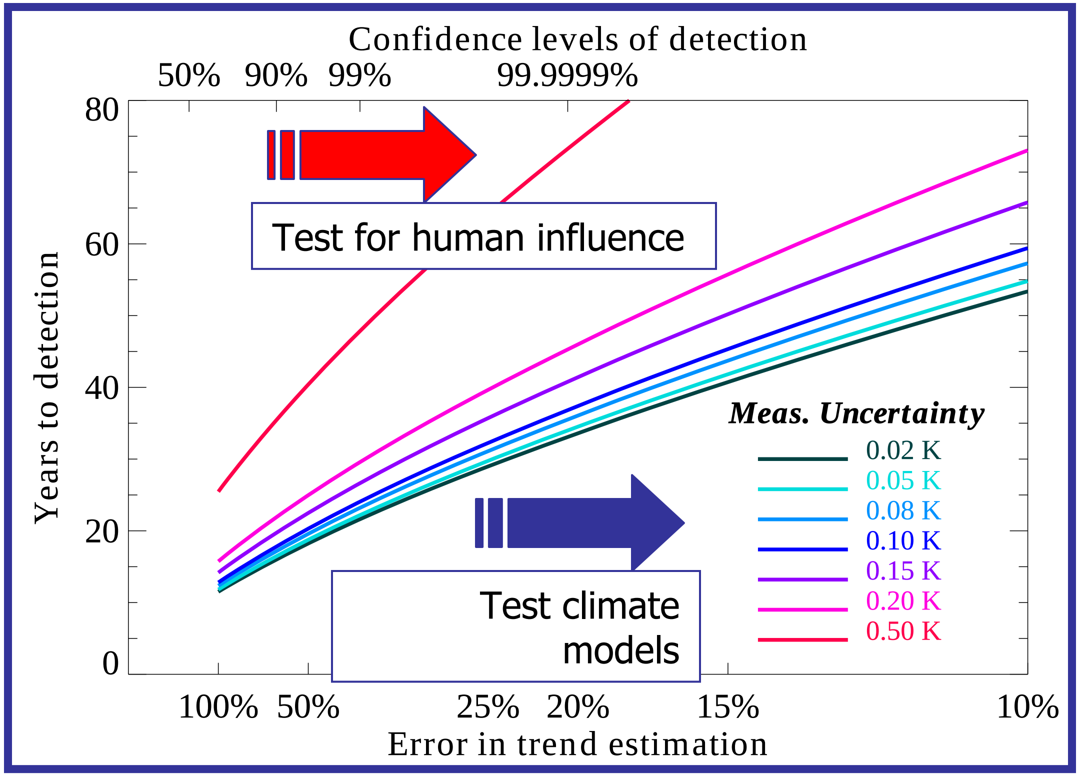
- With observations traceable to international standards, one evaluates the uncertainty (accuracy) of individual measurements in a timeseries.
- Any timeseries of climate data includes both natural variability with standard deviation σ_v, timescale τ_v, and measurement uncertainty (σ_m and τ_m).

With a timeseries of length Δt, the uncertainty in the determination of the slope determination is

$$\delta m^2 = 12\,(\Delta t)^{-3}\left(\sigma_v^2 \tau_v + \sigma_m^2 \tau_m\right)$$

Leroy, S.S., J.G. Anderson, and G. Ohring, 2008: Climate signal detection times and constraints on climate benchmark accuracy requirements. *J. Climate*, **21**, 841-846.

Measurement Uncertainty & Detection Times



Global temperature at 500 hPa

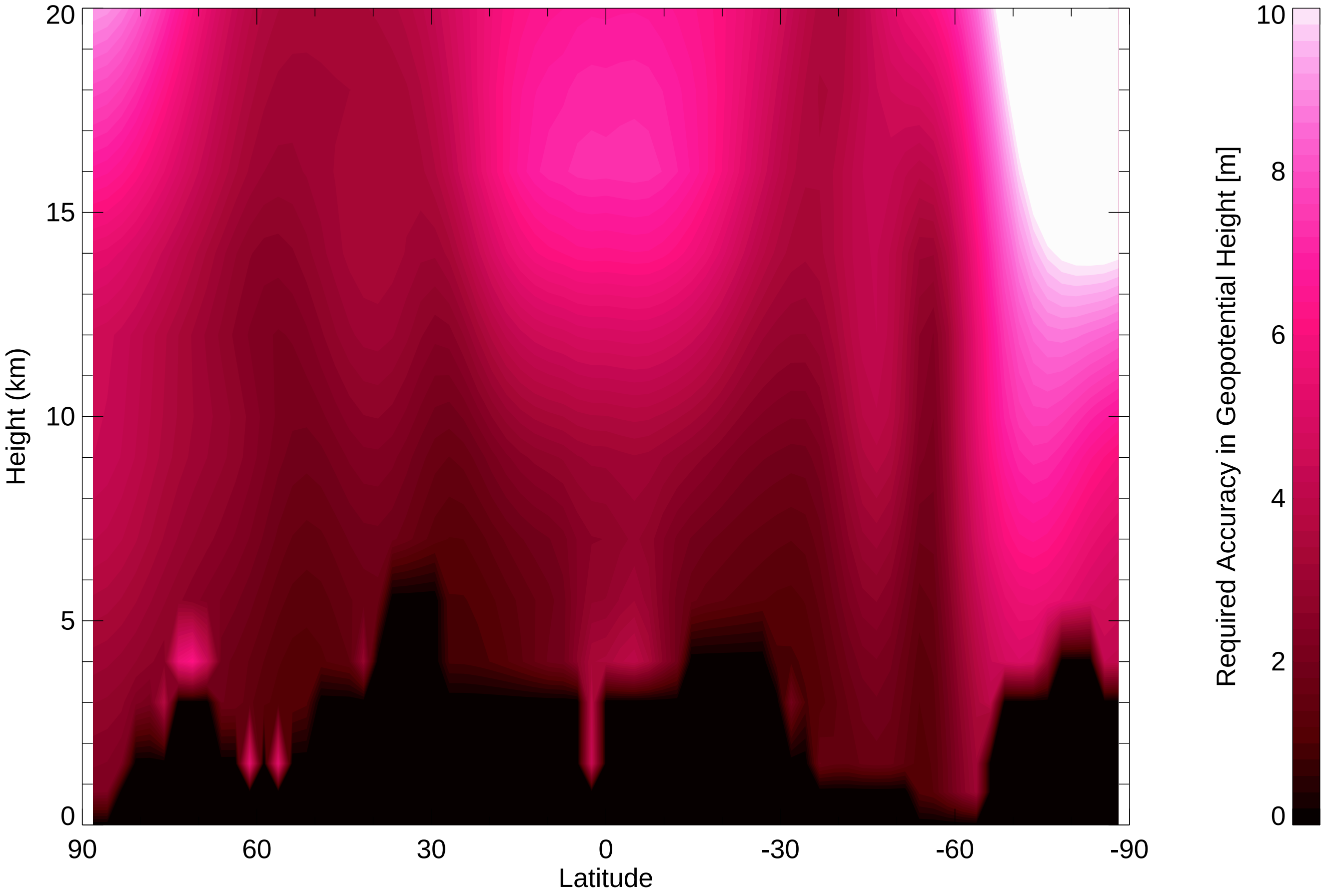
Three satellites, 6-year lifetime.

Natural variability: 0.18 K, 1.54 year correlation time (UKMO HadCM3), Trend: ~0.2 K decade^{-1}.

Optimization has the effect of lowering the entire family of curves.

GNSS RO, 6-yr Mission

Accuracy requirements for a 6-yr mission, based on UKMO HadCM3 control



Summary

- GNSS RO has the unique capability of measuring thermal expansion of the troposphere
- First signal detected is poleward migration of baroclinic zones
- Accuracy requirement for lower troposphere is a few parts in 10^4 for refractivity
- Accuracy requirements for stratosphere yet to be determined.

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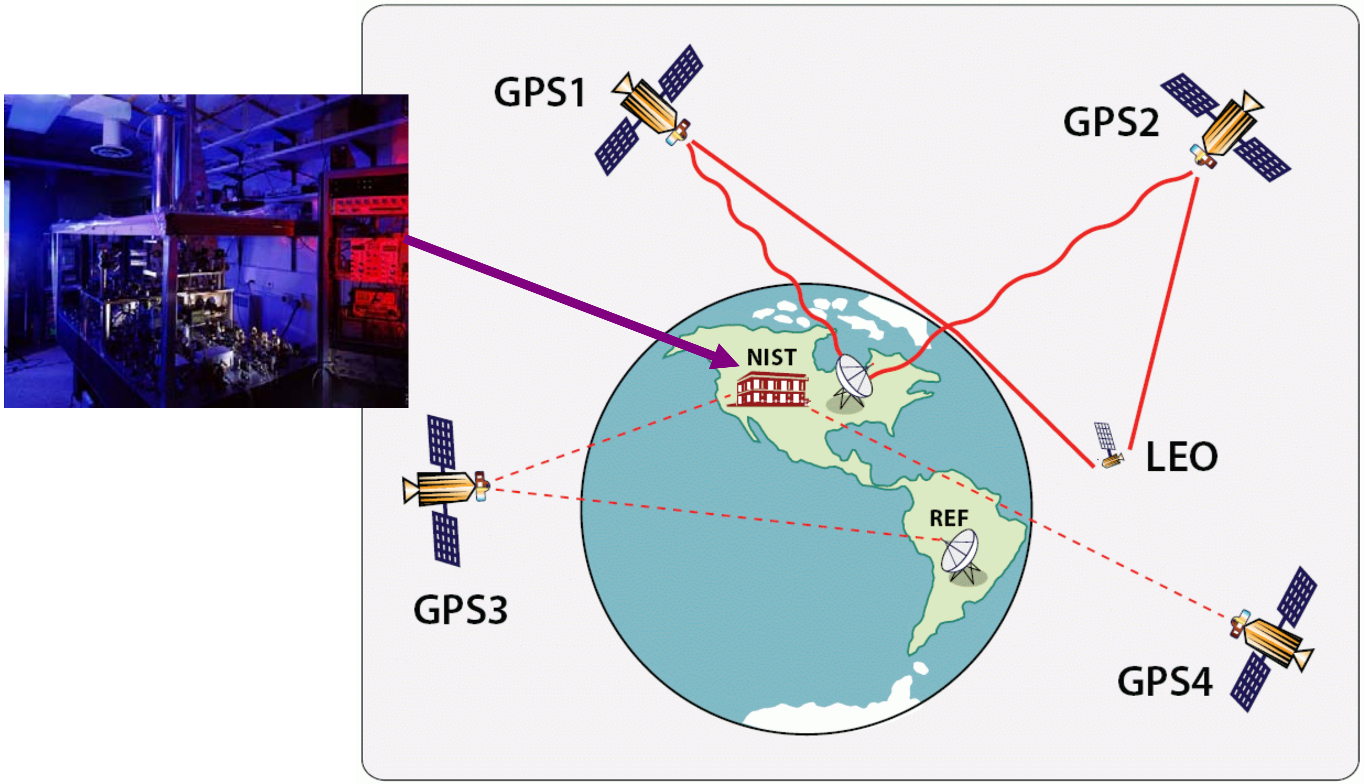
Extra Slides

Sources of Error?

- Testing by inter-mission comparison
  - CHAMP vs SAC-C
  - CHAMP vs COSMIC
- Testing by inter-center trend comparison
  - Ho et al.: Dominant error is sampling error, a random term. Primary cause is quality control.
  - Natural to better understand QC for GPS RO, but may not be necessary for climate.
- Residual ionosphere:
  - Large scale?
  - Scintillation and nonlinearity?

Calibration: SI Traceability



Double differencing

Hardy, K.R., G.A. Hajj, and E.R. Kursinski, 1994: Accuracies of atmospheric profiles obtained from GPS occultations. *Int. J. Sat. Comm.*, **12**, 463-473.

Thermal Infrared Spectra