Analyzing Clear Sky AIRS data for evidence of stochastic forcing

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Motivation

- AIRS has given us 12+ years of high quality TOAradiance data
- Data probes all levels of atm, in different dynamic regions eg T(z), O3(z), WV(z), surface
- Accurate clear sky and scattering models allow us to compare AIRS observational data with GCM model fields; first moment (biases) and second moment (standard deviations) are primary indicators of GCM accuracy
- Even under "clear sky" conditions, probability distribution functions (PDFs) from AIRS data are non-Gaussian; evidence of power law tails (extreme events)
- Linear Stochastic Forced Models (LSF) predict relationship between skewness and kurtosis, as well as power law tails
  - $K \geq 3/2S^2 - r$
  - power law behavior in tails $pdf(x) = x^{-\alpha}$ for large x
  - atmospheric/ocean data eg SST, sea level height, 300 mb vorticity shows evidence of this
- Focus of talk : look at AIRS obs/ clearsky cals using ERA, MERRA model fields, for evidence of stochastic forcing

PDF Moments

Mean, StdDev, Skewness, Kurtosis are the 1st,2nd,3rd,4th moments of the (normalized) PDF

$$< x >= \mu = \int p(x) x dx$$

$$\sigma^2 = \int p(x)(x-\mu)^2 dx$$

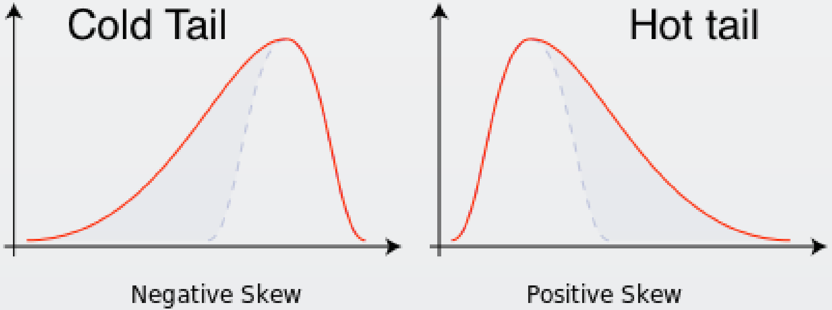
$$S = \frac{1}{\sigma^3} \int p(x)(x-\mu)^3 dx$$

$$K = \frac{1}{\sigma^4} \int p(x)(x-\mu)^4 dx$$

Gaussian : skewness = 0, kurtosis = 3

Review of PDF Moments

"More stuff on right" or "cold tail extending to left" : Skewness < 0
"More stuff on left" or "hot tail extending to right" : Skewness > 0



Sharply peaked distribution (less in the tails) : Kurtosis > 3
Wider distribution (more in the tails) : Kurtosis < 3

Previous work on atmospheric/ocean data : Examples

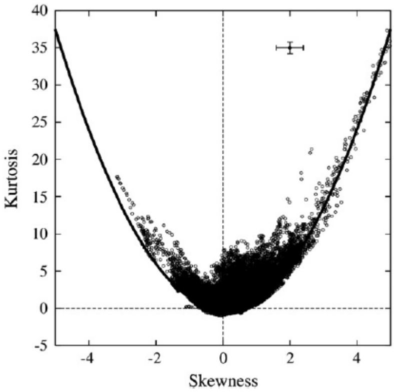


Fig. 4. Scatter plot of excess kurtosis versus skewness for full-year SST anomalies equatorward of 65° North and South. The solid line denotes the function $K=(3/2)S^2$. The estimated local 95% confidence intervals on the values are indicated in the upper right corner of the figure.
Adapted from Sura and Sardeshmukh (2008).

Stochastic modeling

Fast and slow dynamics are separated, with fast scales modeled as random noise processes:

Multiplicative noise in stochastically forced models can be shown to reproduce non-Gaussian statistics and power law behavior in PDF tails

$$\frac{dx}{dt} = -a(x(t)) + Ex(t)\eta(t) + g\eta(t) \quad (1)$$

where a = deterministic slow processes, while E x(t) η represents state dependent multiplicative noise [as opposed to state independent additive noise $g\eta(t)$]; $\eta(t)$ is Gaussian white noise

PDFs derived from SDE have the $K \geq \frac{3}{2}S^2 - r$ relationship and power law tails $pdf(x) = x^{-\alpha}$ for large x

Approach

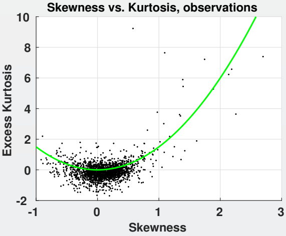
- Bin monthly AIRS BT clear sky obs (night over oceans) data into $4^\circ \times 4^\circ$grids
- Similarly bin clear sky calcs using ERA and MERRA model fields using SARTA-clear
- Create plots of skewness ($S =< x^3 > / \sigma^3$) vs. excess kurtosis ($K =< x^4 > / \sigma^4 - 3$)
- Analyze the PDFs in regions with high skewness and kurtosis, where a power law structure is expected in the extremes.
  - Focus on "hot" tails
  - Focus on slopes $\alpha < 10$ so look for extreme events above gaussian tail

AIRS Channels Analyzed

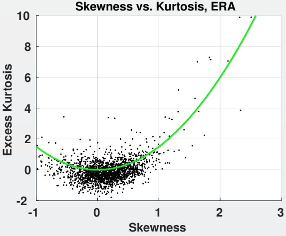
- Channel 54 (662 cm^{-1}): Upper stratospheric temperature
- Channel 359 (754 cm^{-1}): Mid-tropospheric temperature
- Channel 1055 (1024 cm^{-1}): Stratospheric ozone
- Channel 1291 (1231 cm^{-1}): Surface temperature and clouds
- Channel 1475 (1344 cm^{-1}): Lower tropospheric humidity
- Channel 1614 (1420 cm^{-1}): Upper tropospheric/lower stratospheric humidity

662 cm^{-1} (Strat T(z))

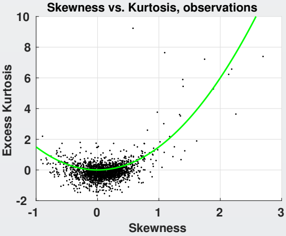
Obs



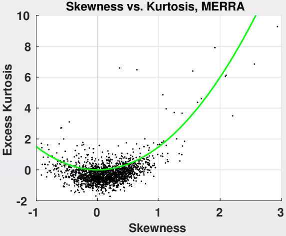
ERA



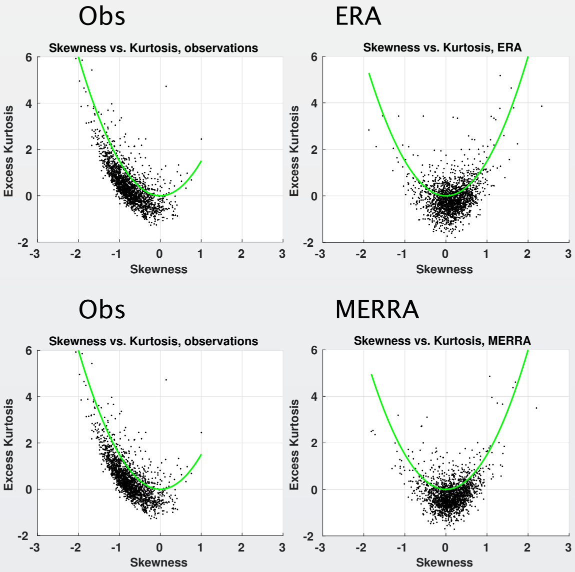
Obs



MERRA

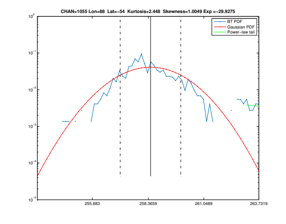


1024 cm^{-1} (Ozone)

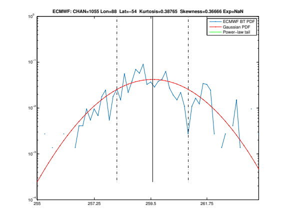


1024 cm^{-1} (Ozone) Power law tail

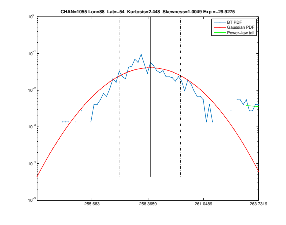
Obs



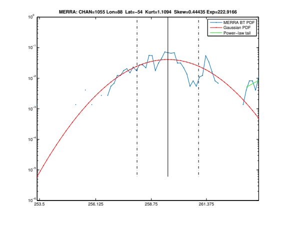
ERA



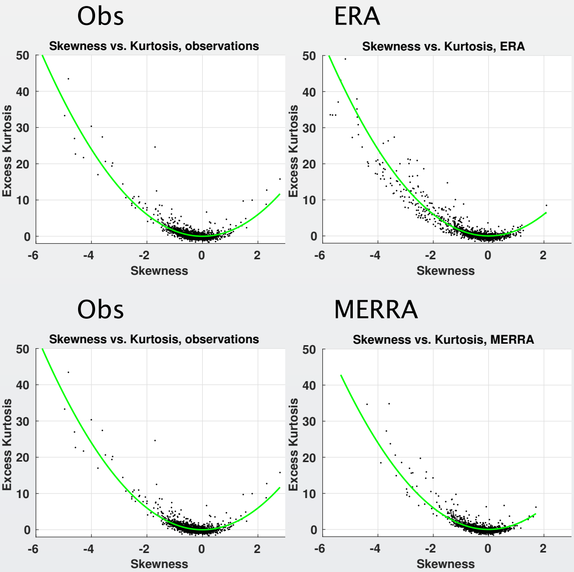
Obs



MERRA

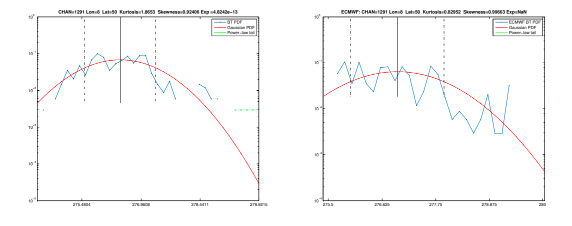


Channel 1231 cm^{-1} (Window)

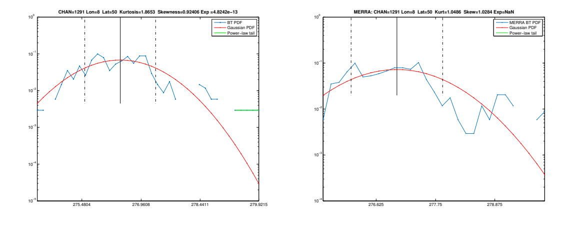


Channel 1231 cm^{-1} (Window) Power Law Tail

Obs ERA

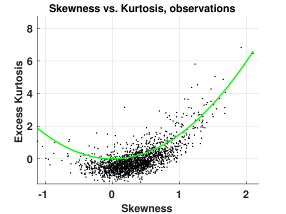


Obs MERRA

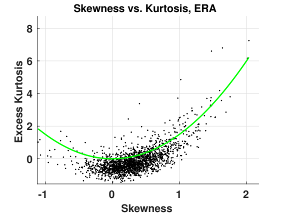


Channel 1420 cm^{-1} (UT WV)

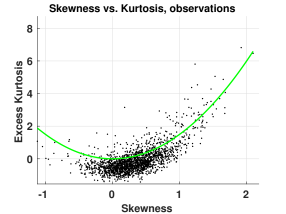
Obs



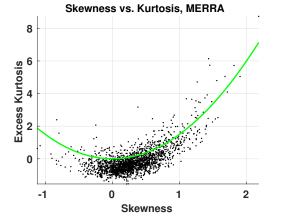
ERA



Obs

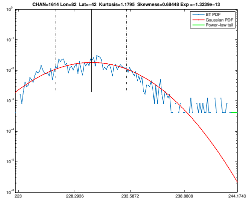


MERRA

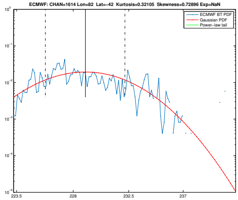


Channel 1420 cm^{-1} (UT WV) Power Law Tail

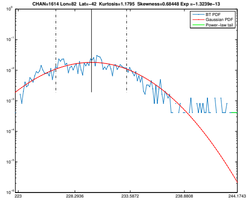
Obs



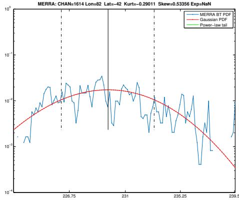
ERA



Obs



MERRA



Short Summary

- Strat T is "quiet" (as we expect)
  - most PDFs have ExK=0, S=0 so they are gaussian
  - Obs, and ERA/MERRA both show some pdfs with S=2,K=6
- Ozone channel shows Obs are skewed negative (high altitude, so should not be clouds) but the models much more Gaussian on avg
  - Hot tail can be seen in Obs data, but not models
- Window Channel : don't see hot tail in models.
- UT WV Channel : also no hot tail from models
- Remember for eg O3 channel, Obs were usually more skewed than ERA/MERRA calcs. We focused on some of these gridboxes when looking for extremes, and found that in many of them, Obs showed extreme events while Cals did not

Numerical Simulations of SDE

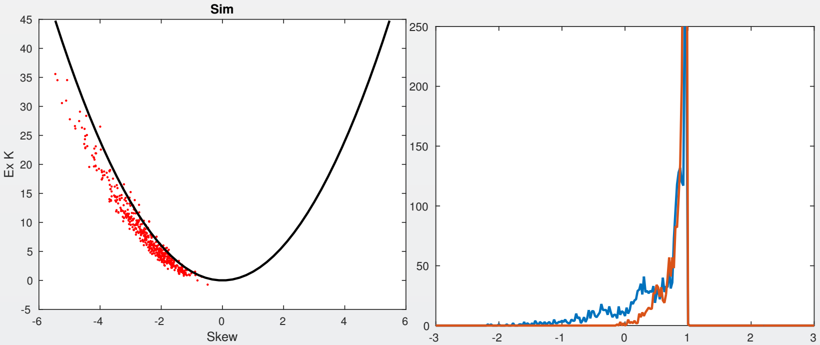
- Simple stochastic models to help interpret the analysis of AIRS data in terms of stochastic forcing.

$$dx(t) = -Ax(t)dt + (Ex(t) + g)dW \tag{2}$$

where y is a scalar function of time only, A, E, g are constants

  - A nonzero, E,g = 0 : damped behavior
  - g nonzero, A,E = 0 : random walk (Brownian motion)
  - Need E non-zero to reproduce quadratic behavior, and power law tails
- AIRS skewness/kurtosis relationships obtained by varying the multiplicative stochastic forcing ($Ex(t)$) and the additive stochastic forcing.
  - By changing eg E, you can shift the bulk of the distributions so it becomes negatively or positively skewed

$A = 0.01, E = -0.5, g = +0.5$



- LH panel : K vs S for ensemble simulation of SDE equation
- RH panel : couple of PDF examples from the ensemble, using the entire time simulation interval (10 units)
  - if we broke these into eg 4 pdfs of length 2.5 units, you can see how we can model slowly evolving pdfs

Conclusions

- AIRS observations as well as ERA and MERRA reanalysis exhibit statistical features that indicate the presence of stochastic forcing.
- Skewness/Kurtosis plots indicate that perhaps a weak multiplicative forcing is occurring. This is reinforced by simulations of a scalar SDE with varying strength in the multiplicative noise term.
- Extreme events are captured in the power law regions of the PDFS where non-Gaussian behavior can be observed.
- Differences between AIRS observations and ERA and MERRA reanalysis are largest in the extreme power law region of the PDFs, indicating the the reanalysis may be missing some of the extreme events.