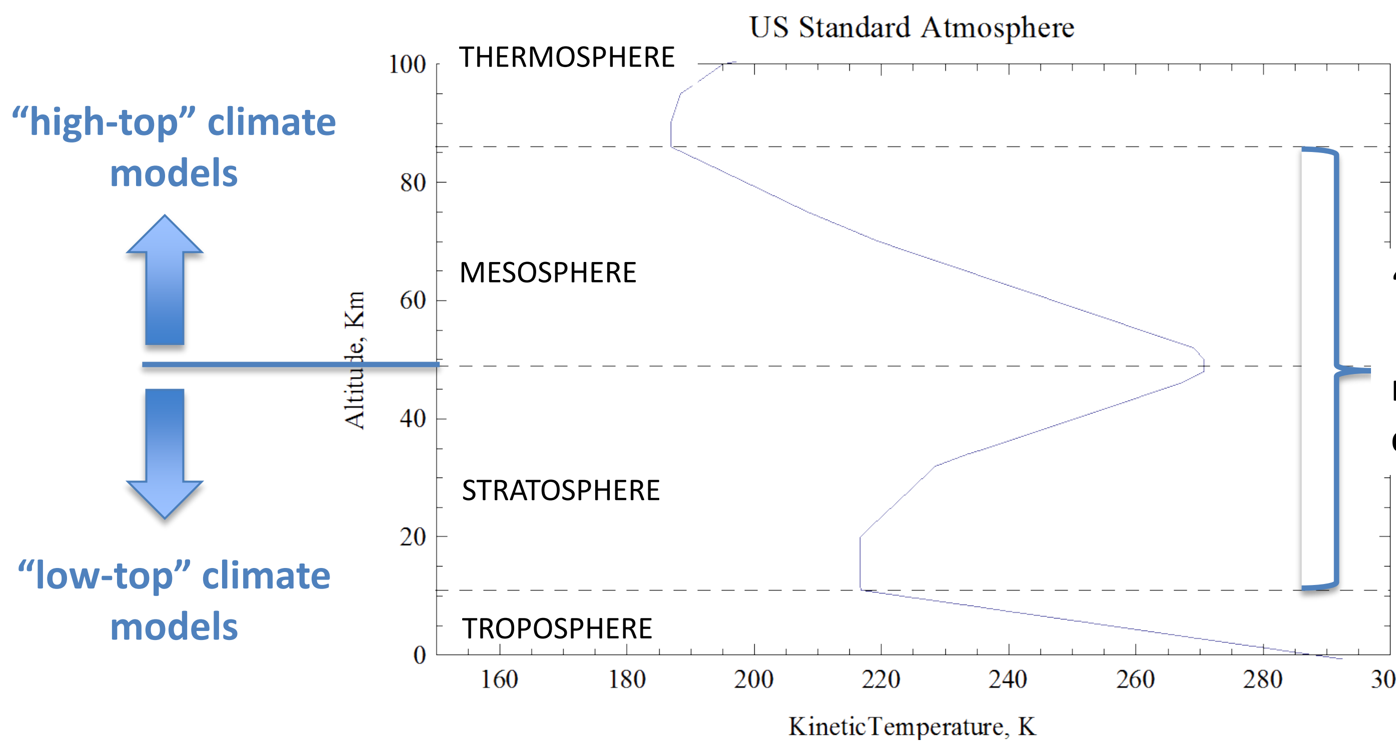
CMIP in the Stratosphere < covey1@llnl.gov >

Basic Vocabulary

CMIP = Coupled [ocean-atmosphere-climate] Model Inter-comparison Project

Stratosphere = second-lowest layer of the atmosphere; layers separated by local maxima / minima of temperature as a function of altitude



“Middle atmosphere” (= stratosphere + mesosphere) has T-max created by O_3 heating.

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Key 2013 Papers Assessing Stratospheric Performance of the CMIP5 Models

Eyring V., et al. (2013) "Long-term **Ozone** Changes and Associated Climate Impacts in CMIP5 Simulations," *J. Geophys. Res. 118*, 5029–5060, doi:10.1002/jgrd.50316

Charlton-Perez A. J. et al. (2013) "On the Lack of Stratospheric Dynamical Variability in Low-top Versions of the CMIP5 Models," *J. Geophys. Res., 118*, 10.1002/jgrd.50125

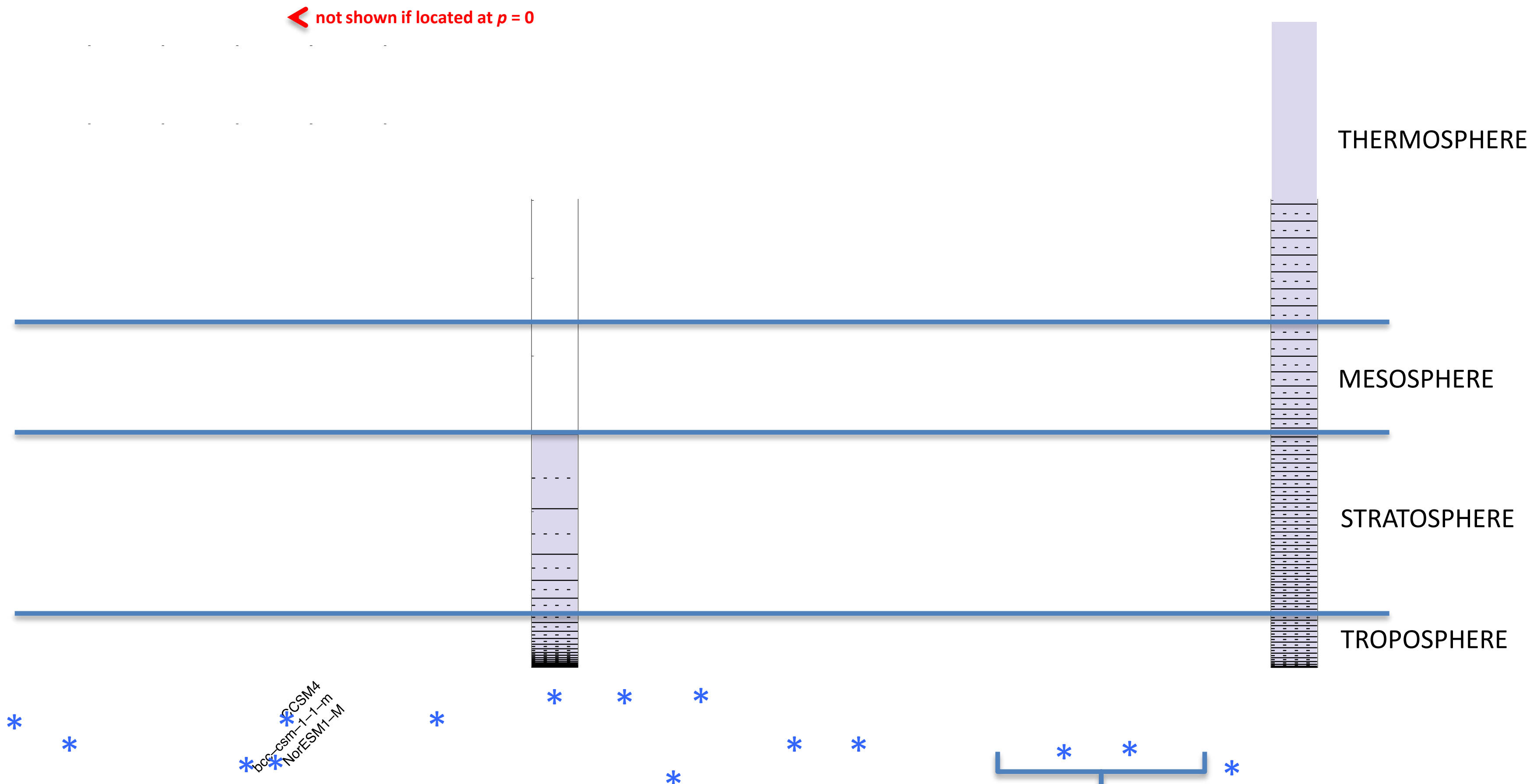
- **General assessment of T and dynamics for 10 hPa < p < 1000 hPa**: computed simulated-vs.-observed difference, correlation and r.m.s. error for q, T, u in 21 models*

Kawatani Y. & Hamilton K. (2013) "Weakened Stratospheric **Quasi-Biennial Oscillation** Driven by Increased Tropical Mean Upwelling," *Nature 497*, 478-481

My 26 models = their 21 + 5 extras (CESM-WACCM, CanESM2/AM4, HadGEM2-A, MPI-ESM-MR).

Vertical Levels in 26 CMIP5 Models [17 include 3-hr surface output*]

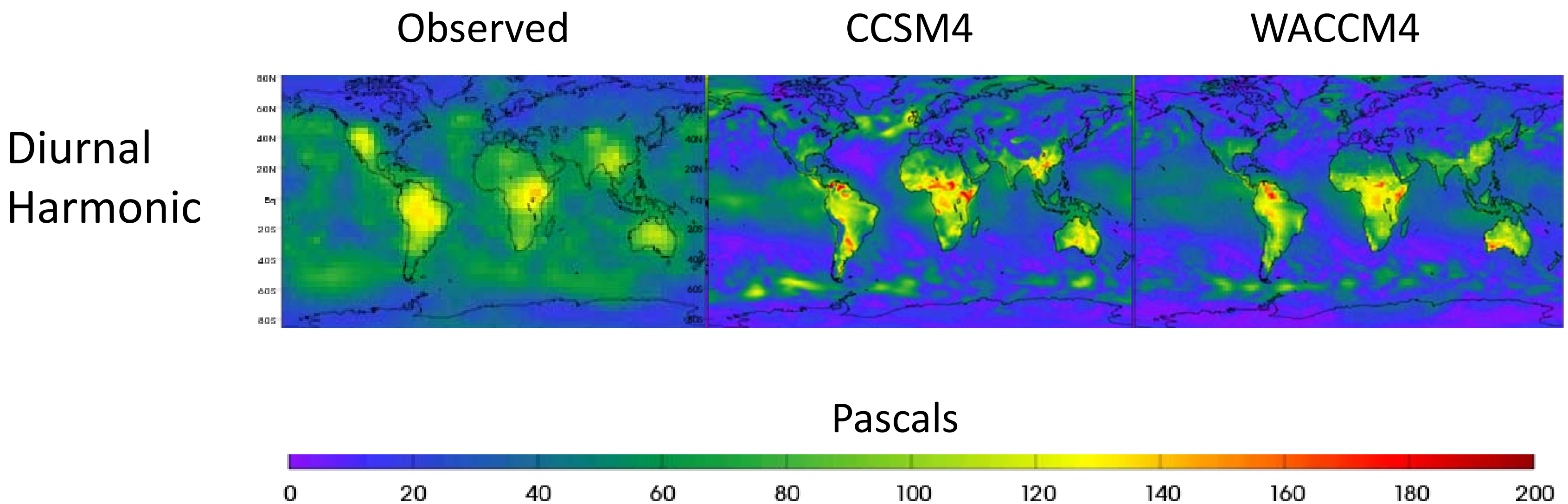
- 17 / 26 models include all of the stratosphere
- 10 / 26 models include all of the stratosphere + all of the mesosphere



NOTE: In CMIP3 the fractions were:
5 / 23 all-stratosphere
0 / 23 all-stratosphere+mesosphere
(Cordero and Forster 2010)

"The four models in CMIP5 that realistically simulate the QBO" (Kawatani and Hamilton 2013; they note that CESM1-WACCM also simulates a realistic QBO but uses nudging to do so).

Surface-Pressure Amplitudes of Atmospheric Tides in Observations* and Two CESM Models**

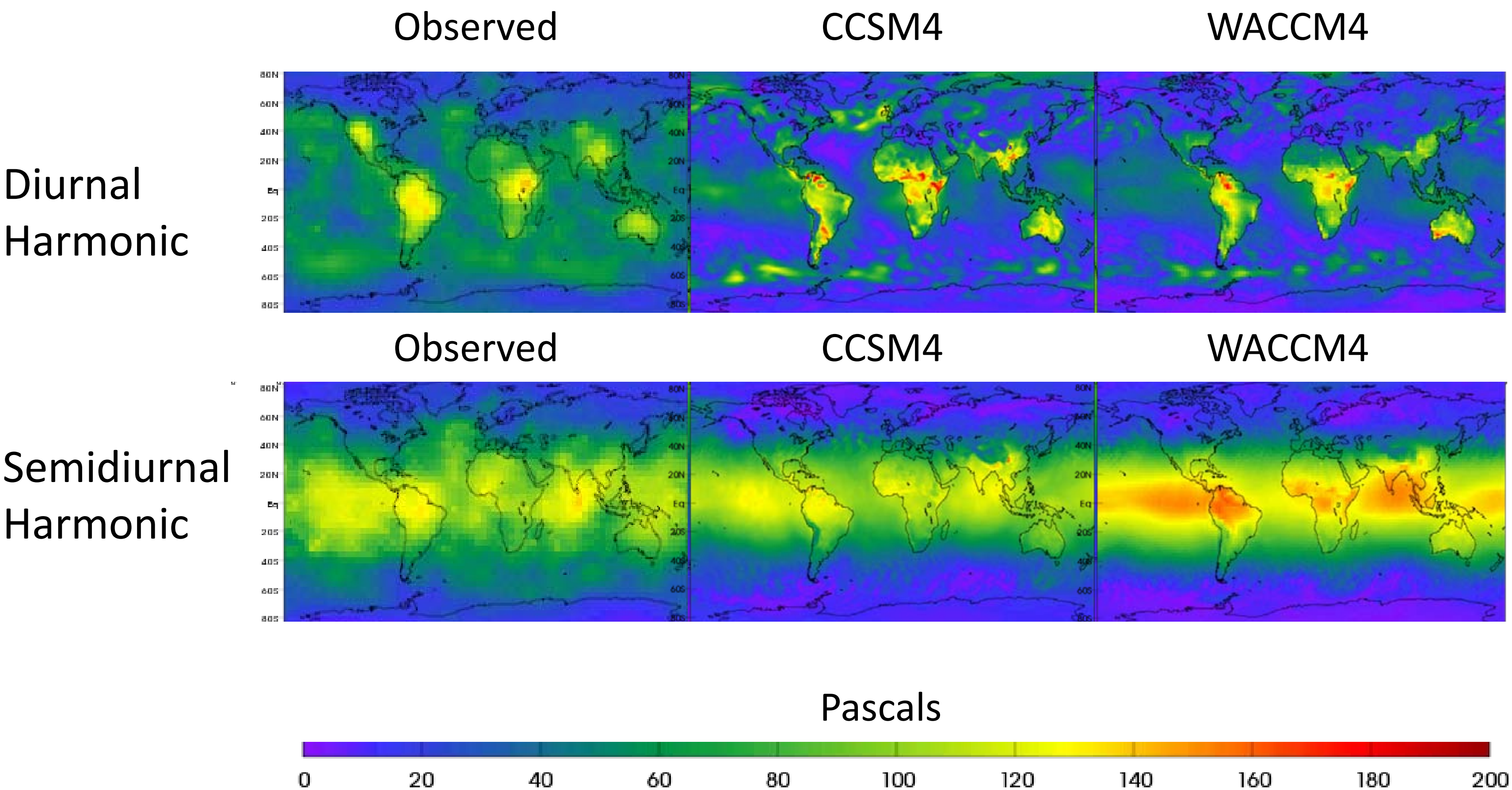


Like the diurnal cycle of surface temperature, the <u>diurnal harmonic</u> of surface pressure is forced by tropospheric heating: H_2O(v) absorbing solar energy, latent heat release . . .

* A. Dai and J. Wang, 1999: "Diurnal and Semidiurnal Tides in Global Surface Pressure Observations, *Journal of the Atmospheric Sciences,* **56,** 3874-3890

** C. Covey, A. Dai, R. S. Lindzen, D. R. Marsh 2014: "Atmospheric Tides in the Latest Generation of Climate Models," in revision for *Journal of the Atmospheric Sciences*

The <u>semidiurnal harmonic</u> is forced by O_3 heating in the middle atmosphere . . .



. . . so the model with a complete middle atmosphere (WACCM4) gets a bigger amplitude. But apparently, compensating errors are occurring.

Our papers show that *all* CMIP models overestimate semidiurnal amplitude. Compensating errors may be common!

Q: What sort of compensating errors could the models have in their tide simulations?

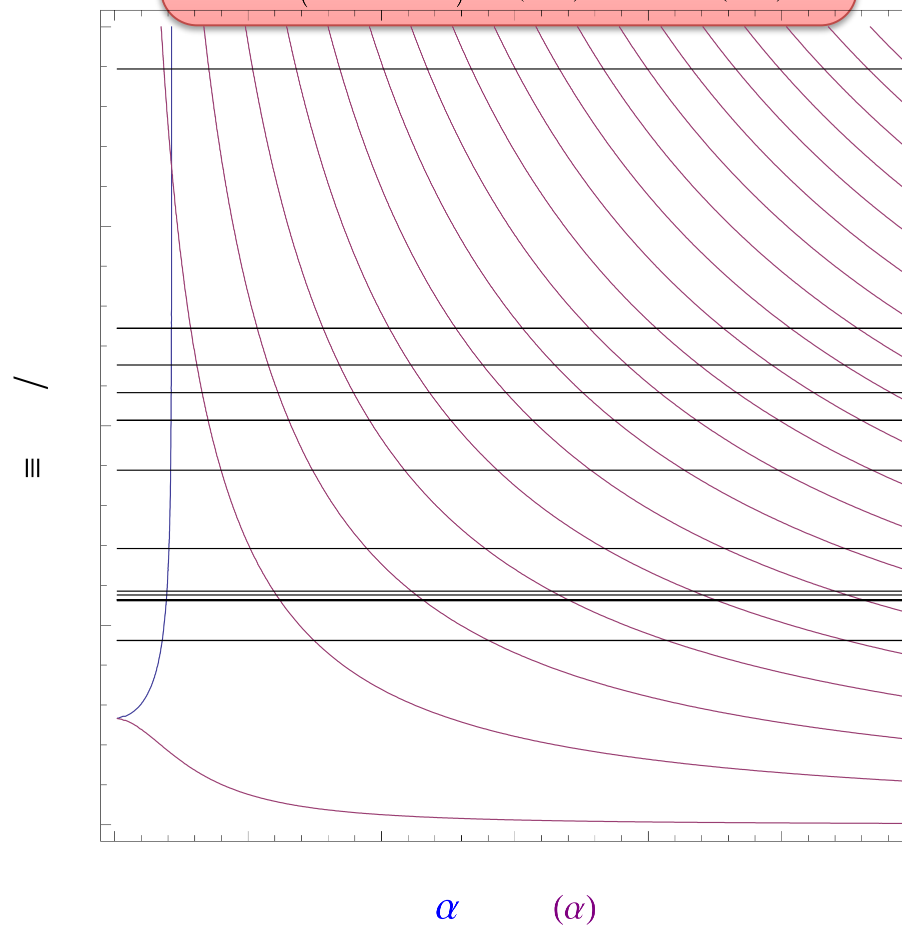
$$G(x) = A\, e^{\alpha x} + e^{-\alpha x} \Rightarrow$$

$$\frac{d^2 G}{d x^2} = \left(\frac{1}{4} - \frac{\kappa H}{h}\right) G \equiv \alpha^2 G = 0$$

A: One possibility involves reflection of waves from the top of the model:

From Lindzen et al. (1968): "when the atmosphere has an artificial top then there are an infinite number of *h*'s for which [the vertical structure equation] has nontrivial solutions ... These constitute the free oscillations of the atmosphere; they include Rossby-Haurwitz waves. In an infinite atmosphere these are all associated with a single *h* ... [but] bounded models will have other Rossby-Haurwitz waves associated with the spurious *h*'s."

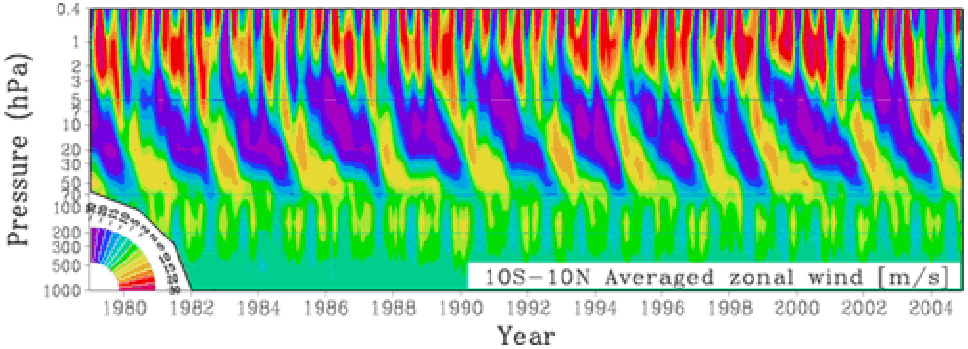
(Horizontal lines show positions of the top-most "full levels" in 17 CMIP5 models.)



REFERENCE: R. S. Lindzen, E. S. Batten and J.-W. Kim, 1968: "Oscillations in Atmospheres with Tops," *Monthly Weather Review,* **96,** 133-140

The Quasi-Biennial Oscillation in Microwave Sounding Unit data

- QBO traditionally defined by the mean zonal wind ➔➔➔
- . . . but also has a temperature component ≤ 3 – 5 K.



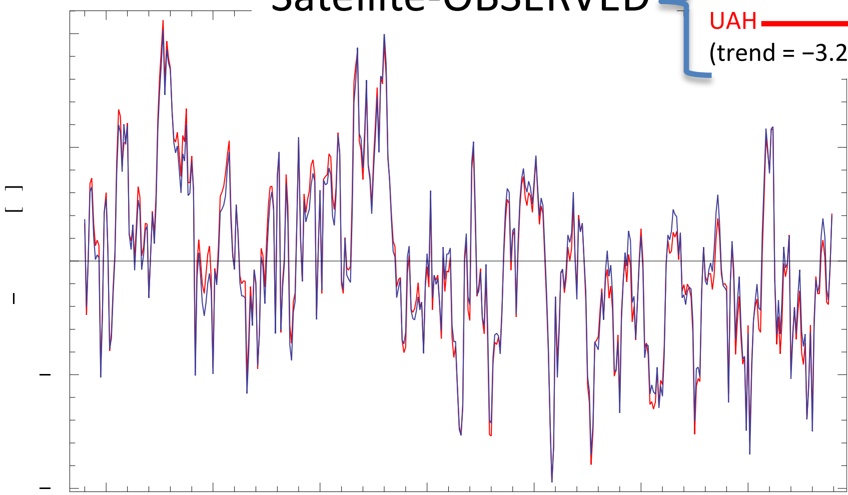
- Therefore, can complicate T-trend analysis in tropical upper troposphere.
- QBO signal appears in MSU temperatures after filtering / EOFs (Christy & Drouilhet 1994: *J. Climate 7*, 106; Fernandez et al. 2004: *J. Climate 17*, 3934).
- Now emerges directly from a VERY simplistic Fourier analysis of the complete 1979-2013 time series.

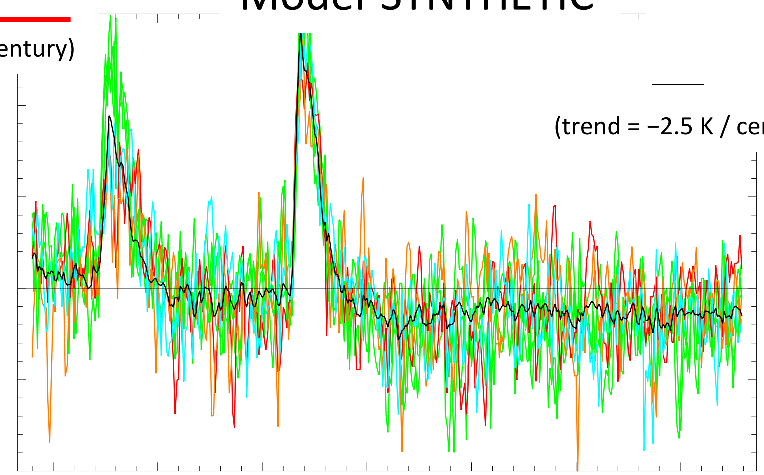
*Graphic from http://jra.kishou.go.jp/**JRA-25**/JRA25quality_en.html (2008)

MSU Temperatures in the Tropical Lower Stratosphere
(weighting function peak ≈ 70 hPa; 20°S – 20°N area average)

Thanks to Ben Santer for data.

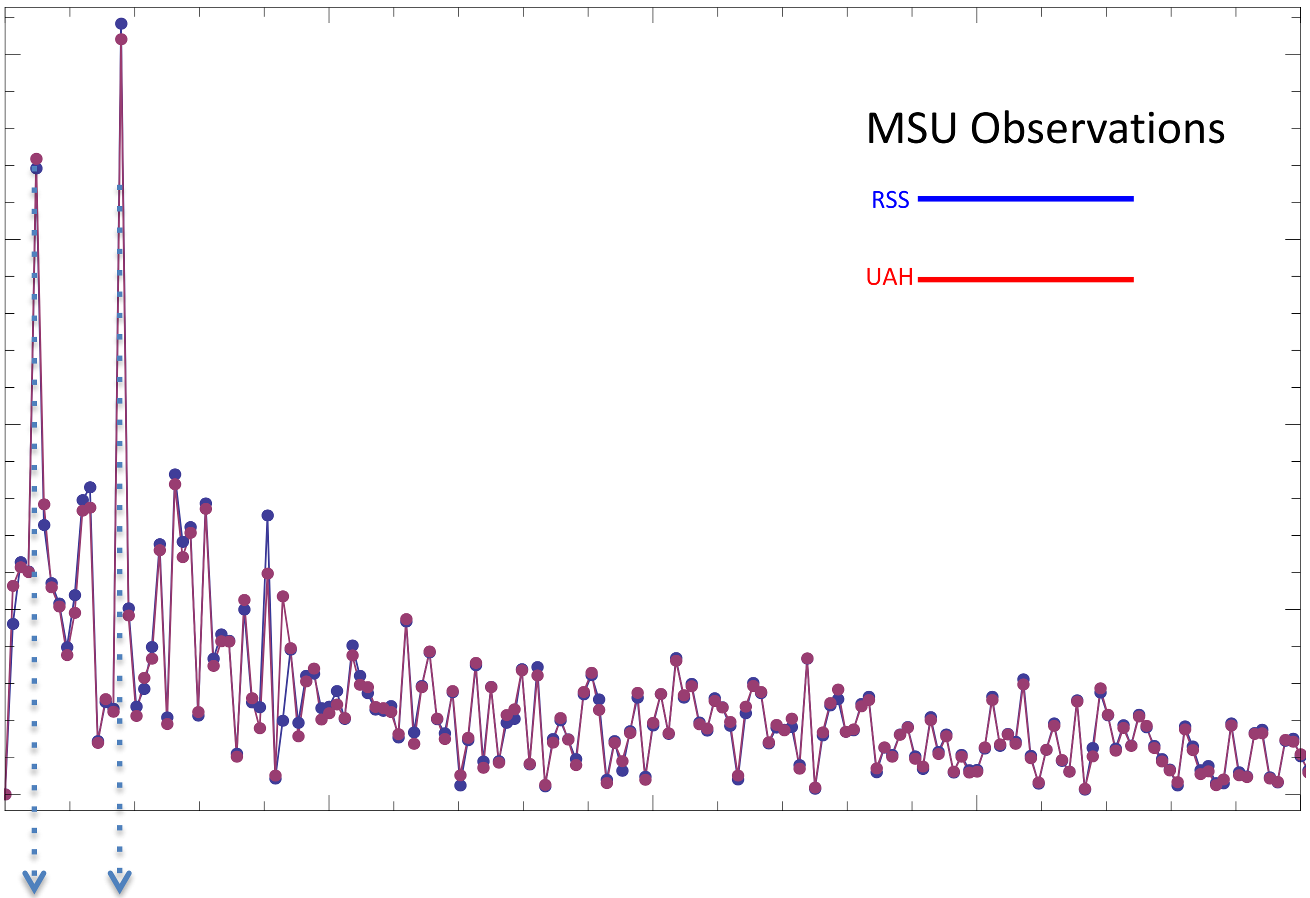
FOR OBSERVATIONS: Superimposed on a steady decline are times of elevated temperatures around 1983 (El Chichon), 1992-3 (Pinatubo), 1997-2000 (El Nino?) and 2011 (La Nina??). These occur roughly once a decade. Also apparent are temperature spikes occuring at roughly two-year intervals -- by definition “quasi-biennial.”



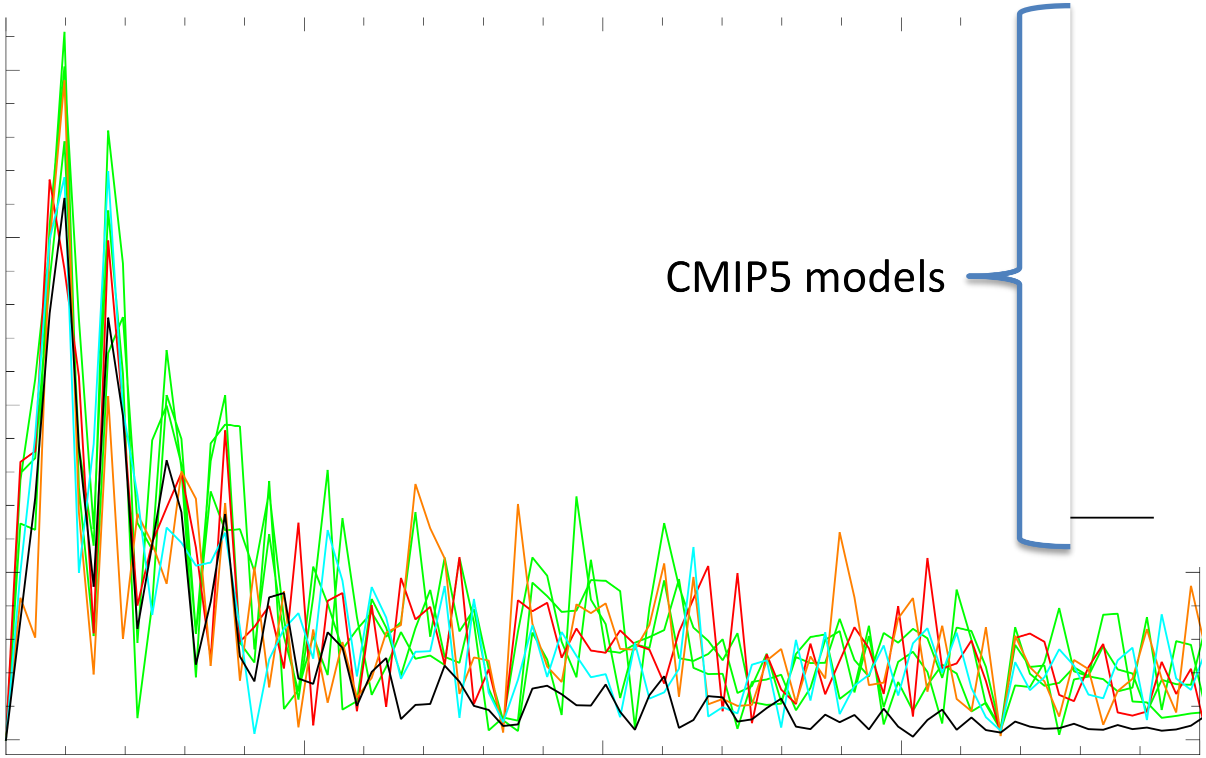


Fourier analysis:

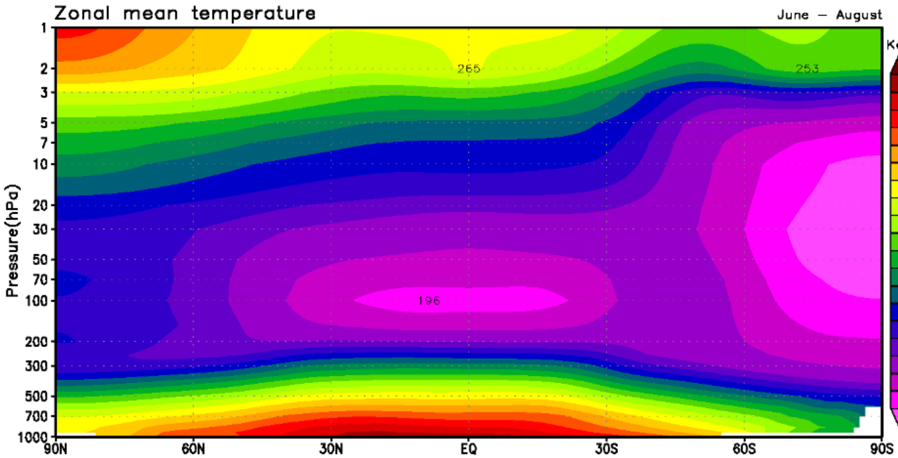
$$T_m = \sum_{s=-N/2+1}^{N/2} a_s\, e^{2\pi i s m/N}, \; m = 1, 2, 3, \; \ldots, N.$$

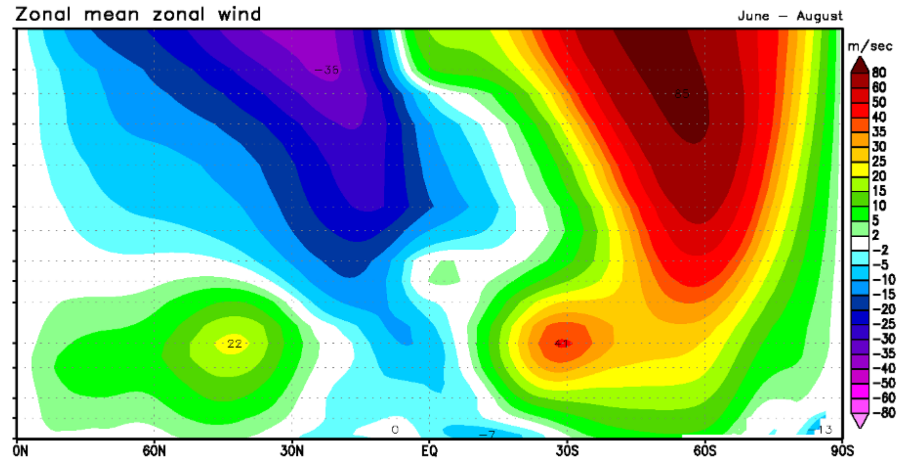


Periods: 105 28 (months)


CMIP5 models

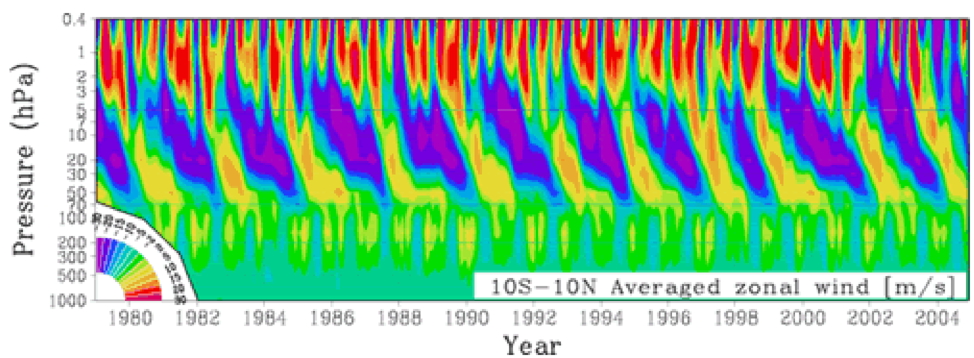
Observations of Structure and Dynamics*





"Cold tropical tropopause and midlatitude *T*-max in the lower stratosphere in the winter hemisphere"
"Rather uniform *T*-increase from winter pole to summer pole in the 30 – 60 km layer" [$p \approx 1$ hPa]
"Reversed *T*-gradient above 60 km [$p < 0.2$ hPa] with *T* increasing from summer to winter pole"
"Intrusion of summer hemisphere easterlies into the winter hemisphere"
"Displacement of axis of the winter hemisphere westerly jet to about 60° (the polar night jet)"

"Semiannual oscillation of *u* has its maximum amplitude near the equatorial stratopause."
"Very strong oscillation of *u* and *T* in the tropical lower stratosphere which has a somewhat irregular period, averaging about 26 months. Alternating pattern of downward propagating easterlies and westerlies."



*Graphics from http://ds.data.jma.go.jp/gmd/jra/atlas/eng/indexe_isobar13.htm and jra.kishou.go.jp/JRA-25/JRA25quality_en.html (2008). Quotes: Holton, *Dynamic Meteorology of the Stratosphere and Mesosphere* (1975).
The fundamental observations are robust from the rocketsonde era to the satellite / reanalysis era.

Q: Do results from other CMIP models also imply compensating errors?

A: Definitely! All of them over-predict semidiurnal tide amplitude independent of their vertical coverage:

Lowest-top models (30km)

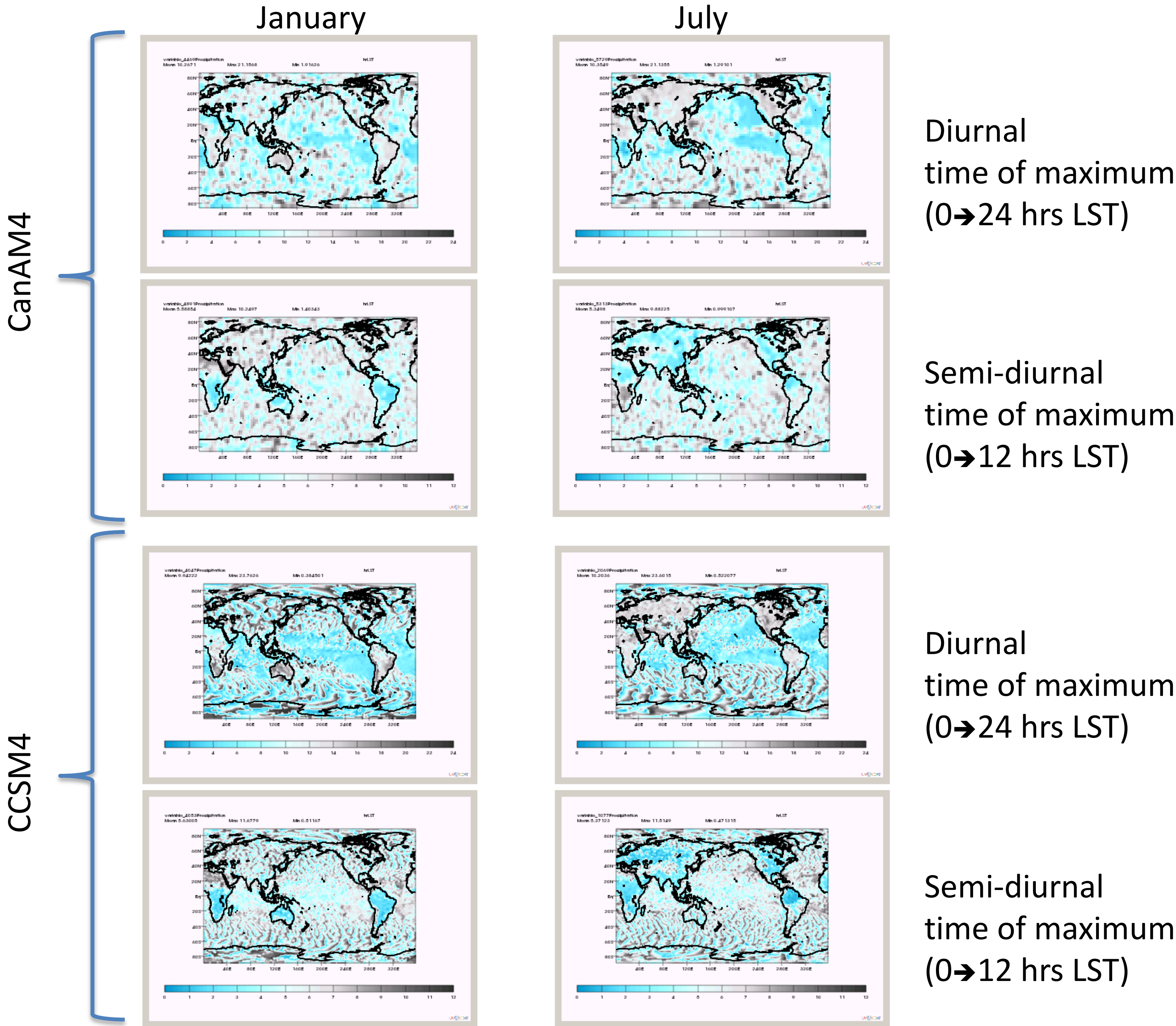
WACCM4

CCSM4

Thick black line: observations

Thin lines + symbols: CMIP5*

*For CMIP3 see Covey et al., 2011: "The Surface-Pressure Signature of Atmospheric Tides in Modern Climate Models, *Journal of the Atmospheric Sciences,* **68,** 3874.


January
July
CanAM4
CCSM4
Diurnal
time of maximum
(0→24 hrs LST)
Semi-diurnal
time of maximum
(0→12 hrs LST)
Diurnal
time of maximum
(0→24 hrs LST)
Semi-diurnal
time of maximum
(0→12 hrs LST)