Summary of the
Climate Dialogue
on
the (missing) tropical hot spot

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Introduction

Based on theoretical considerations and simulations with General Circulation Models (GCMs), it is expected that any warming at the surface will be amplified in the tropical upper troposphere. More warming at the surface means more evaporation and more convection. Higher in the troposphere the (extra) water vapour condenses and heat is released. IPCC published the following figure in its fourth report (AR4) in 2007:

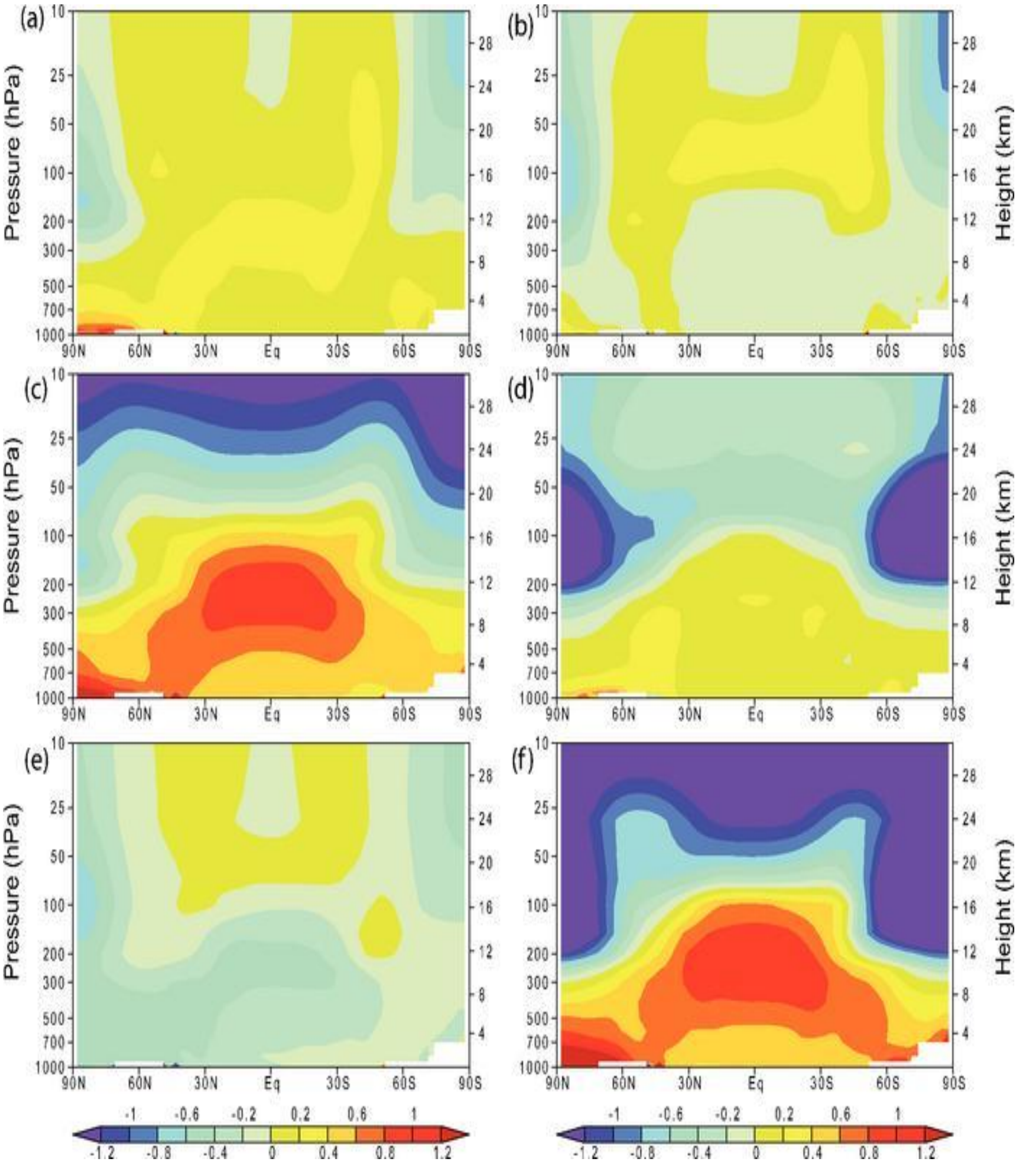

Figure 1. Repeat of figure 9.1 from AR4. Zonal mean atmospheric temperature change from 1890 to 1999 (°C per century) as simulated by the PCM model from (a) solar forcing, (b) volcanoes, (c) well-mixed greenhouse gases, (d) tropospheric and stratospheric ozone changes, (e) direct sulphate aerosol forcing and (f) the sum of all forcings. Plot is from 1,000 hPa to 10 hPa (shown on left scale) and from 0 km to 30 km (shown on right). See Appendix 9.C for additional information. Based on Santer et al. (2003a).

Source: http://www.ipcc.ch/publications_and_data/ar4/wg1/en/figure-9-1.html

The figure shows the response of the atmosphere to different forcings in a specific GCM (called PCM). The IPCC report adds that "*the major features shown in Figure 9.1 are robust to using different climate models*". As the figure shows, over the past century, the greenhouse forcing was expected to dominate all other forcings. The expected warming is highest in the tropical troposphere, dubbed the tropical hot spot. The discrepancy between the strength of the hot spot in the models and the observations has been a controversial topic in climate science for almost 25 years. Some claim that observations show less warming in the tropical troposphere and therefore the hot spot is "missing".

Do the discussants agree that amplified warming in the tropical troposphere (i.e. the hot spot) is expected?

To be short, the discussants **agree** on this topic.

However in the course of the dialogue it turned out that different definitions of the "hot spot" were being used. The agreement noted above is limited to the "strict" definition of the "hot spot" which is just the fact that warming at the surface will be amplified higher up in the tropical troposphere. So the key word here is "amplification". A second, broader definition of the hot spot is the fact that models – given the known greenhouse forcing (see figure 1) – expect a lot of warming in the tropical troposphere. So the key term here is "the magnitude of the trend".

Sherwood noted btw that the term "hot spot" was coined by climate skeptic bloggers and not by the scientific community. He and Mears are in favour of the strict definition while Christy focuses more on the broader definition as is shown in table 1 and 2. The controversy surrounds mainly the broader definition of the hot spot, the fact that models simulate a high warming trend in the tropical upper troposphere while observations show much less warming.

Table 1

	Sherwood	**Christy**	**Mears**
Is amplified warming in the tropical troposphere expected?	Yes	Yes	Yes
Is the magnitude of the warming trend in the tropical troposphere included in your definition of the hotspot?	No	Yes	No

Can the hot spot in the tropics be regarded as a fingerprint of greenhouse warming?

Here again the short and simple answer is "no" from all participants. However, later in an email to Climate Dialogue Christy wrote that he regards the hot spot as "a" fingerprint and that our question was not well posed. It appears that on the one hand Christy acknowledges that the tropospheric amplification is not specific to a GHG mechanism, but on the other hand he maintains that the magnitude of the tropospheric temperature trend indicates that the GHG influence on warming is less than expected (by the models). This is related to slightly different interpretations of the terms "hot spot" and "fingerprint".

Christy wrote in his guest blog: "*So, what has the extra CO_2 and other greenhouse gases done to the climate as of today? Climate model simulations indicate that a prominent and robust response to extra greenhouse gases is the warming of the tropical troposphere (…)*"

So for him a lack of warming in the tropical troposphere would falsify the models and could indicate that the effect of greenhouse gases is not so large.

Mears and Sherwood used a stricter interpretation of the term fingerprint (i.e. implying "specificity") in their guest blog and comments along with an interpretation of the hot spot as referring to the amplification of surface warming in the tropical troposphere. Since this amplification is expected whatever the cause of warming is, they don't see why this should be such a controversial topic and why people use it to imply something about the relative role of greenhouse gases specifically.

We reflect these differences between Christy and Sherwood/Mears in the third row of table 2.

Table 2

	Sherwood	**Christy**	**Mears**
Can the hot spot in the tropics be regarded as a specific fingerprint of greenhouse warming?	No	No	No
Do climate model simulations indicate that extra greenhouse gases give a prominent warming of the tropical troposphere?	Yes	Yes	Yes
Would a lack of warming in the tropical troposphere have serious implications for attribution of global warming to GHG?	No	Yes	No

Is there a significant difference between modelled and observed amplification of surface trends in the tropical troposphere (as diagnosed by e.g. the scaling ratio)?

Both *Sherwood* and *Mears* **agree** this question cannot be answered because the observations are not stable enough over time to determine whether a hot spot exists or not, or is as prominent as we would expect. This is in part due to the added noise that one gets when calculating the ratio of two small, relatively similar, uncertain numbers. Ross McKitrick, a well-known sceptical scientist, who published several papers about the hot spot, agrees with Sherwood and Mears. In a public comment he wrote: "*The statistical issues involved in figuring out the distributions of ratios of random numbers get complicated quickly, and I wouldn't be surprised if the problem is intractable.*"

Christy though has published evidence that the amplification factors differ significantly between nearly all models and observations in the CMIP-3 models, a result which he also found with the updated CMIP-5 models used here. In their ensemble averages, the models and observations are clearly significantly different.

A lengthy and quite technical discussion followed between Mears and Christy about what is the best metric for tropical upper tropospheric temperature trends and also what datasets are best. Mears is in favour of the so-called Temperature Tropical Troposphere (TTT) while Christy prefers the Temperature of the tropical Mid-Troposphere (TMT).

Mears indicates that TMT, as directly observed by the Advanced Microwave Sounding Units (AMSU) on board of satellites, is not really the mid-tropospheric temperature because it also includes part of the lower stratosphere. Since the stratosphere is cooling it tends to cancel some of the tropospheric warming. Therefore, TTT should be used which adjusts for this cooling effect.

Observational TTT trends are slightly higher than TMT trends and the same can be said for those trends in the models.

During the dialogue we noted that Christy seemed to prefer *warmer* datasets and Mears *cooler* datasets. Even when they discussed trends of one specific dataset, Christy generally came up with lower trends than Mears. To resolve this we prepared table 3 in which we summarise lots of trends of different datasets and metrics. During this process Mears and Christy converged to the point where hardly any difference remained.

What could explain the relatively large difference in tropical trends between the UAH and the RSS dataset?

As can be seen in table 3 the trend differences between the UAH and RSS datasets[i] are quite large in the tropical troposphere. Globally UAH and RSS trends are quite similar for the lower troposphere (TLT). The UAH trend since 1979 is even slightly higher than the RSS trend. However for TMT the agreement is much less, both in the tropics and globally. Mears and Christy agree that compensating errors seem at play. They noted that the difference is likely related to different diurnal adjustments and is not easily resolved.

Christy is therefore in favour of taking the average of UAH and RSS. Sherwood was opposed to this idea because similar reasoning would lead to the conclusion there is no longer any doubt about equilibrium climate sensitivity, because the average of the models and of various estimates based on past data are each around 3^0C.

So although many issues remain about the different datasets, at the end of the day both Mears and Christy agree that the big picture is quite clear. Models show more warming than the observations, both for TMT and TTT.

Table 3 Tropical tropospheric temperature trends since 1979

Data source	**Temp Type**	**^{0}C/decade Christy**	**^{0}C/decade Mears**
RSS v3.3	TMT	0.088	0.086 ± 0.04
UAH v5.6	TMT	0.031 ± 0.05	0.033
RSS+UAH	TMT	0.060 ± 0.03	0.060 ± 0.03
STAR3.0[a]	TMT	0.106	0.102
All satellites[b]	TMT	0.075	0.074
HadAT2	TMT	Not Updated through 2013	
Raobcore	TMT	0.055	0.058
RICH	TMT	0.087	0.100
RATPAC	TMT	0.016	Not Adjusted After 2005
Radiosondes	TMT	0.049 ± 0.035[c]	0.079[d]

74 models	TMT	0.26	0.278[e]
RSS	TTT[f]	0.123	0.121
UAH	TTT	0.068	0.067
STAR3.0	TTT	0.145	0.144
All Satellites	TTT	0.112	0.111
HadAT2	TTT	Not Updated through 2013	
Raobcore	TTT	0.081	0.085
RICH	TTT	0.128	0.135
RATPAC	TTT	0.071	Not Adjusted After 2005
102 models	TTT	0.316	0.330[g]

[a] During the dialogue there was much discussion about the reliability of STAR2.0; STAR3.0 though is accepted by both Christy and Mears.
[b] Including STAR3.0.
[c] Based on Raobcore, RICH and RATPAC
[d] Based on Raobcore and RICH
[e] Based on 33 model runs.
[f] TTT = 1.1*TMT - 0.1*TLS where TLS is Temperature of the Lower Stratosphere.
[g] Based on 33 model runs.

Table 3 *Tropical tropospheric temperature trends based on different radiosonde and satellite datasets for the period 1979-2013 and the area 20S-20N. TMT=Temperature of the tropical Mid Troposphere, TTT=Temperature of the Tropical Troposphere. Note that this table was made a year after the actual dialogue together with active input from Christy and Mears.*

Table 4

	Sherwood	Christy	Mears
Is there a significant difference between modelled and observed amplification of surface trends in the tropical troposphere?	Data too uncertain to answer this question	Yes	Data too uncertain to answer this question
What satellite product should be used?	x	TMT[a]	TTT[b]
Is STAR a reliable additional dataset?	x	STAR3.0 is more reliable than STAR2.0	Yes
Are UAH and RSS tropical troposphere trends significantly different from each other?	x	Yes	Yes
What is likely the main reason for the difference between the UAH and RSS TMT trends?	x	Diurnal adjustments	Diurnal adjustments

[a] TMT=Temperature of the tropical Mid Troposphere
[b] TTT=Temperature Tropical Troposphere

Are models warming significantly faster than the observations?

For Christy this was the key issue. He wrote: "*The simple numbers tell the story and can't be overlooked. From 73 CMIP-5*[ii] *model runs, the 1979-2012 mean tropical TMT trend is +0.26 °C/decade. The same trends calculated from observations, i.e. the mean of four balloon and mean of two satellite datasets, are slightly less than +0.06 °C/decade. (…) The mean of the models (often used as the ´best estimate´ in IPCC assessments) and observations differ by +0.20 °C/decade which is highly significant.*"

Mears in a comment agreed the difference is significant: "*Measured trends in the tropical troposphere are less than all of the modelled trends (or almost all in the case of STAR 2.0). This is an important, statistically significant, and substantial difference that needs to be understood.*" Later Mears wrote in an email: "*The observed tropical trends are outside the range predicted by almost all models.*"

Sherwood never wrote explicitly that the difference between models and observations is significant. He wrote: "*I think we all agree that recent warming in the Tropics has been less than we would have expected no matter how it is measured, and I agree this merits further research.*"

In the introductory article of this Climate Dialogue we mentioned the hot spot debate that lasted for years and was subject of two papers by Douglass et al (of which Christy was a co-author) and Santer et al (of which Mears and Sherwood were co-authors) in 2008[iii]. At the time Douglass et al claimed a statistically significant difference between models and observations. Santer et al. disagreed and said Douglass et al underestimated the uncertainties of both the observations and the models and that the differences were not significant. However with more years of data the discrepancy between models and observations has become so large that all participants agree the differences are significant.

So the discussion can now focus on the meaning of this discrepancy between models and observations. For Christy it is key to model fidelity: "*The ´hot spot´, as I stated earlier, represents an integration of much of our understanding of the energy cycle of the climate system. It is the energy cycle that must be well-characterized before attempting to forecast the climate response to a very slight increase in total energy forcing due to the enhanced greenhouse effect.*"

For Mears this is a bridge too far: "*John uses this fact to argue that there are fundamental flaws in all climate models, and that there results should be excluded from influencing policy decisions. This goes much too far.*"

In his guest post Sherwood emphasized there are other model discrepancies that are more interesting, e.g. the decrease in Arctic sea ice that is larger in the observations than in the models. Sherwood assumes sceptics are so focused on the "missing" hot spot because it can be spun into a tale of model exaggeration.

Table 5

	Sherwood	**Christy**	**Mears**
Are models showing significantly more tropical tropospheric warming than observations?	Yes (since 1979) No (since 1958)	Yes	Yes
Is this difference between models and observations an important issue for understanding anthropogenic global warming (e.g. attribution or sensitivity)?	Somewhat, but other model-observation discrepancies are less uncertain and more interesting	Yes, tropical atmospheric temperature is key to model fidelity	Yes, but no reason yet to dismiss the models

What explanation(s) do you favour regarding the apparent discrepancy surrounding the tropical hot spot?

This question almost deserves its own Climate Dialogue. There was not much time left to delve deeply into this matter. But from table 6 one can see that the participants have very different ideas about it. Sherwood's hypothesis is there has been more cooling in the stratosphere than anyone has reckoned and thus the true upper-tropospheric warming could be stronger than what any group now infers from the satellite data. That would mean the data are wrong and that the missing tropical hot spot is hiding in the data.

Christy thinks that, apart from the fundamental problems of the models, there still is a warm bias in the tropical surface temperature record. If the "real" trend at the surface is (much) smaller, the lack of warming in the troposphere fits better with the theory of amplification. However it doesn't change the fact that models overestimate the warming both at the surface and in the troposphere. This discrepancy between models and observations would then become even bigger.

Mears thinks the source of the discrepancy could be the forcings. As an example he mentions that temperature changes in the upper troposphere and lower stratosphere have been shown to be very sensitive to the stratospheric ozone concentrations used. The ozone dataset used in the CMIP5 simulations is the one with the most conservative trends in ozone. If one of the other datasets had been used, the models would have shown less upper tropospheric warming and the hot spot would have been overestimated less.

Table 6

What explanation(s) do you favour regarding the apparent discrepancy surrounding the tropical hot spot?	Sherwood	Christy	Mears
Satellite data show too little warming	Likely	Unlikely	As likely as not
Surface data show too much warming	Very unlikely	Very likely	Unlikely
The theory is not perfect yet due to issues with fundamental model physics (e.g. water vapour and cloud feedback)	Unlikely	Very likely	Unlikely
The solar, ozone and stratospheric aerosol forcings in the CMIP5 models may be wrong	As likely as not	Likely (to some extent)	Likely

Options: don't know, very unlikely, unlikely, as likely as not, likely, very likely)

What consequences, if any, would your explanation have for our estimate of the lapse rate feedback, water vapour feedback and climate sensitivity?

Using the narrow definition of the hot spot (i.e. the amplification) Sherwood concludes the consequences of a missing hot spot for climate sensitivity are nil. However using the broader definition he thinks there could be consequences for climate sensitivity although currently he prefers other possible causes. Sherwood: "*Currently none of the explanations I can see for the 'missing hot spot' would change our estimate of future warming from human activities, except one: that the overall warming of the tropics is simply slower than expected. It does seem that global-mean surface warming is starting to fall behind predictions, and this is particularly so in the tropical oceans (though not, curiously, on land).*"

One option for Sherwood is that negative feedbacks from clouds have kicked in and if true that would revise our estimates of climate sensitivity downward. However currently he favours another hypothesis, namely that oceans are burying heat faster than expected.

Mears gave several reasons for the discrepancy between models and observations. He summarized them in three categories: bad luck, bad forcings and bad model physics. With bad luck he meant that decadal variability which is not well represented by a model mean in reality went the other way. With bad forcings he meant that some forcings are maybe different than we expected. He gave several examples: stratospheric aerosols from volcanic eruptions, solar output, stratospheric ozone and black carbon aerosols. With bad model physics he meant that models are known to have difficulty with such things as clouds and aerosols. "*At this time, we simply do not know the exact cause or causes, but I strongly suspect that it is due to a combination of causes rather than one dominant cause.*"

Christy does think that the lack of warming in the tropical troposphere suggests the climate is relatively insensitive to CO_2 forcing. However he agrees with Mears that we don't know yet why models overestimate the warming so strongly. "*The bottom line is that, while I have some ideas based on some evidence, I don't know why models are so aggressive at warming the atmosphere over the last 34 years relative to the real world. The complete answer is probably different for each model. To answer that question would take a tremendous model evaluation program run by independent organizations that has yet to be formulated and funded.*"

Table 7

	What do you consider the most likely cause for explaining the lack of warming in the tropical troposphere?
Sherwood	Most analyses of radiosonde and satellite data have likely underestimated atmospheric warming
Christy	Water vapour and cloud feedback and therefore climate sensitivity smaller than we thought
Mears	A combination of internal variability, heat subduction into the deep ocean, and solar, volcanic aerosol, and ozone forcing

[i] John Christy is involved in the UAH satellite dataset (University of Alabama in Huntsville) while Carl Mears works for Remote Sensing Systems, a company which has developed the RSS satellite dataset

[ii] CMIP-5 is the Coupled Model Intercomparison Project phase 5. *C*MIP-5 is meant to provide a framework for coordinated climate change experiments and thus includes simulations for assessment in the Fifth Assessment Report of IPCC (AR5) as well as others that extend beyond the AR5.

[iii] Douglass DH, Christy JR, Pearson BD, Singer SF. A comparison of tropical temperature trends with model predictions. Int J Climatol 2008, 27:1693–1701; Santer, B.D.; Thorne, P.W.; Haimberger, L.; Taylor, K.E.; Wigley, T.M.L.; Lanzante, J.R.; Solomon, S.; Free, M.; Gleckler, P.J.; Jones, P.D.; Karl, T.R.; Klein, S.A.; Mears, C.; Nychka, D.; Schmidt, G.A.; Sherwood, S.C.; Wentz, F.J. Consistency of modelled and observed temperature trends in the tropical troposphere. Int. J. Climatol. 2008, doi:1002/joc.1756