Review of: "Intensification of El Niño-induced atmospheric anomalies under greenhouse warming"

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Comments on paper " Intensification of El Nino-Induced atmospheric anomalies under greenhouse warming" by Hu et al (2021)

This is an interesting paper, addressing the important issue of relationships among natural climate variability, specifically ENSO, and greenhouse warming. While the paper was well written and the analyses clear, I would caution against the use of the word "novel" in their statement :"These findings provide a *novel* theoretical constraint for ENSO changes, and for reducing uncertainty in ENSO response to global warming". The use of the Clausius-Clapeyron (CC) relationship governing saturated water vapor to "explain" climate variability and change involving precipitation and moisture and circulation is a common, and often mis-used practice. Apparently, the authors were unaware of many recent studies on changes on radiation-cloud-convection-circulation interaction (RC3I), and feedback to changes in SST and global warming (GW).

- This paper is focused on how ENSO SST induced atmospheric characteristics (temperature, precipitation, humidity and circulation) are energized under GW. The authors claimed that the CC relationship, *i.e.* exponentially increased saturated vapor pressure as temperature (thermodynamics) in a greenhouse warming (GW) climate as the fundamental cause of more energetic atmospheric response to ENSO SSTA. As shown in the following, there is more than just faster rate of increase in saturated water vapor relative to temperature increase, in energizing the response to SSTA.

- The statement " The tropical atmosphere tends to maintain a fixed tropospheric relative humidity (RH) as it warms [Held and Soden 2006]" is out-of-date and incorrect There have been many observational and modeling papers showing that in a warmer climate the global tropospheric RH actually decreases in more places than increases. In fact, under global warming, a global drying signal, *i.e.,* reduced relative humidity (RH) of the tropical upper troposphere, and in the much of troposphere of the subtropics is highly significant [Sherwood et al. 2010, Wright et a. 2010, Held and Shell 2012, Lau and Kim 2015, Su et al. 2017, Lau and Tao 2020, and references therein].

- While the conclusion that that GW intensifies ENSO atmospheric response is essentially correct, the paper's explanation is a gross over-simplification. The paper only emphasized large increase in *saturated* water vapor as a function of temperature due to the CC-relationship. While it is true that warmer SST under global warming generally contributes to increased global specific humidity, changes in atmospheric variables (clouds, precipitation, convection and circulation) are more related to changes in relative humidity, which is a function of both thermodynamics (temperature), and dynamics (moisture transport). This is reflected in the differential form of RH (= q/qs) derivable from the CC-relationship

$$\delta Rh = \delta q/qs - \alpha Rh \delta T$$

From Eq (1), an increase in atmospheric temperature (dT) actually causes a reduction in RH (drying), precisely because the increase in saturated water vapor due to temperature increase is faster than the actual increase in moisture (dq). The change in ambient water vapor (dq) is mainly due to dynamical moisture transport. The balance of the change between dq (dynamics) and dT (thermodynamics) accounts for the moistening of the middle and lower troposphere in the deep tropics, and wide-spread drying in the subtropics and midlatitudes (See Attached Figure). This change in RH pattern has been referred to as the Deep Tropical Squeeze (DTS), featuring an intensified and tightened ITCZ convection and precipitation (over warmer ENSO-like SST maximum near the equator), coupled to an expanding subtropical dry zones, together with a rising tropical tropopause. The DTS signal has been found in ensemble CMIP5 GW simulations, and detected in linear trend (~ 30 years) of ensemble reanalyses data (Lau and Kim 2015, Su et al., 2017, Lau and Tao, 2020). The DTS is a fundamental mechanism of atmospheric feedback involving R3CI, even in the absence of SSTA, as shown in super-parameterized GCM simulations with climatological SST (Lau et al. 2019).

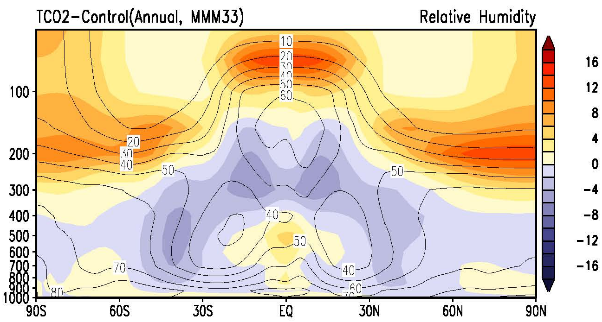

Figure 1. Long-term trend signal in zonal mean relative humidity (%) in 2x CO2 ensemble simulations from 33

CMIP5 models. From Lau and Kim (PNAS, 2015)

- As shown in their paper (Hu et al. 2021), natural modes of climate variability (NCV) such as ENSO can be energized by GW. On the other hand, it can also be construed that changing NCV contribute to GW signal. This is why SSTA under GW has distinct regional structural similarities to NCV, such as ENSO, PDO, AMO etc. Because of the global climate system is nonlinear, NCV and GW climate signals are intricately linked, and need to be considered as such, in interpreting results of model simulations and observations.

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