Parameterization development at high resolution in atmospheric models utilizing both idealized and realistic model configurations

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Final Report

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Summary

We have constructed and analyzed a series of idealized models of tropical convection interacting with large-scale circulations, with 25-50km resolution and with 1-2km cloud resolving resolution to set the stage for rigorous tests of convection closure schemes in high resolution global climate models. Much of the focus has been on the climatology of tropical cyclogenesis in rotating systems and the related problem of the spontaneous aggregation of convection in non-rotating systems. The PI (Held) will be delivering the honorary Bjerknes lecture at the Fall 2016 AGU meeting in December on this work. We have also provided new analyses of long-standing issues related to the interaction between convection and the large-scale circulation: Kelvin waves in the upper troposphere and lower stratosphere, water vapor transport into the stratosphere, and upper tropospheric temperature trends. The results of these analyses help to improve our understanding of processes, and provide tests for future high resolution global modeling. Our final goal of testing new convections schemes in next-generation global atmospheric models at GFDL has been left for future work due to the complexity of the idealized model results meant as tests for these models uncovered in this work and to computational resource limitations. 11 papers have been published with support from this grant, 2 are in review, and another major summary paper is in preparation.

Objectives and focus

A hierarchy of idealized modeling frameworks: A primary focus of this proposal is on devising a hierarchy of models with which to study the interaction between moist convection and large-scale circulations, exemplified by the problem of understanding the controls on the statistic of tropical cyclones. Model simulations include horizontally homogeneous radiative-convective equilibrium (RCE), both rotating and non-rotating; and aqua-planet simulations.

Processes in the tropical upper troposphere: Of particular interest are the connections between waves in the tropical upper troposphere and in the stratosphere; processes in the tropical upper troposphere that control the depth of deep convection; the upper tropospheric temperature response to increasing greenhouse gases; the associated changes in high clouds; the role of the upper troposphere temperature trends on the intensity of tropical cyclones, and the connections between sea surface temperature trends and upper tropospheric trends.

Results

(1) Tropical cyclone climatology in idealized models

We (Co-Pi Held with Zhou, Ballinger, and Merlis) have performed a distinctive series of simulations of tropical cyclone formation and structure in idealized geometries that have provided important new insights into the climatology of tropical cyclone (TC) statistics. All of these models are constructed by simplifying a comprehensive GCM (GFDL HiRAM) that produces a realistic simulation of the spatial and seasonal structure of TC genesis and its interannual variability, The variety of behaviors observed in these idealized models has been startling. Held will be delivering the honorary Bjerknes lecture at the Fall 2016 AGU meeting in December on this work. He will also be the senior author of a paper currently in preparation reviewing this work and outlining the open questions raised (Held et al 2016).

1a) Tropical cyclones in idealized horizontally homogeneous models

Led by Wenyu Zhou, rotating radiative-convective equilibrium (RRCE) has been studied by removing the spherical geometry of the HiRAM atmospheric model and placing it in a doubly periodic horizontally homogeneous f-plane geometry, using a 25 km grid. In the first study (Zhou et al, 2014), the sea surface temperatures are prescribed to be constant. In all cases examined the model fills up with densely packed tropical cyclones, indicating that this TC-dominated regime is the end state to which the tropical atmosphere tends unless prevented by the consequences of horizontal inhomogeneities. The natural “outer scale” of the TCs, determining how many storm can co-exist in this closely-packed configuration, ncreases with decreasing rotation rate and increasing SSTs. The "inner scale" of the TCs, the radius of maximum surface wind, although only marginally resolved, increases with SST but, unlike the outer scale, increases with increasing rotation rate. We believe these are the first simulations of TCs in which the radius of maximum winds is seen to vary systematically with change in parameters. An important technical result is that these parameter dependencies can be modified or even reversed if the domain is smaller than the storm's natural outer scale, emphasizing the importance of studying these parameter dependencies in large domain. The parameter study provides a reference point for analogous future studies with cloud resolving models.

In a second study (Zhou et al , under review) a similar RRCE study is conducted with a lower boundary condition consisting of a static slab of water -- a simple way of allowing the surface temperatures to change while conserving energy. The depth of this "slab ocean" is varied systematically to see how the storm statistics change. The expectation was that TCs would weaken with decreasing slab depth since there would be less energy for the TC to tap and SSTs would drop beneath the storm, preventing it from intensifying. Instead, we find very little change in intensity as a function of slab depth. Standard theories for TC intensity fail to describe this behavior. All cases continue to generate a regime of closely packed storms, regardless of the lower boundary condition.

(1b) Tropical cyclones in aqua-planet configurations

Merlis et al (2013) have also idealized the HiRAM model retaining spherical geometry but removing continents and the seasonal cycle, using an energy consistent slab ocean. Tropical precipitation and the ITCZ latitude are manipulated by imposing a heat source in the slb in high latitudes of one hemisphere and a heat sink in high latitudes of the other hemisphere.. The dependence of tropical storm statistics on the latitude of the ITCZ is then studied, the result being a very rapid increase in TC genesis with increasing ITCZ latitude. As one increases CO2 or solar insolation in this model, the number of TCs increases, in contrast to the "mother" HiRAM model (and most other realistically configured models, which show a decrease with warming.) The model's ITCZ moves poleward with warming. When the ITCZ is the source of most of the disturbances that ultimately form TCs, as in this aquaplanet configuration, the ITCZ movement can control the global TC frequency. When the ocean heat flux amplitude is adjusted to compensate for the ITCZ displacement due to warming, simulated hurricane frequency decreases under warmed conditions, consistent with most comprehensive model projections of twenty-first century global tropical cyclone frequency. These results have encouraged several other modeling groups to study aquaplanet configurations of their models to see how the latitude of the ITCZ moves with increasing CO2, given a control climate in which the ITCZ is off the equator.

Ballinger has led a study of aquaplanet configurations of the same model but with prescribed SSTs, allowing a finer control of the SST distribution. Ballinger et al (2015) describes simulations with zonally symmetric SSTs. An example of the intriguing results is that a flatter latitudinal SST distribution in the tropics results in fewer TCs (contrary to some speculations in the paleoclimate literature), but these TCs are more intense. This and other results in the paper provide a variety of challenges for the development of genesis indices meant to summarize the environments favorable for TC genesis. Held et al (2016) will also describe simulations with this model in which SSTs are a function of longitude as well as latitude.

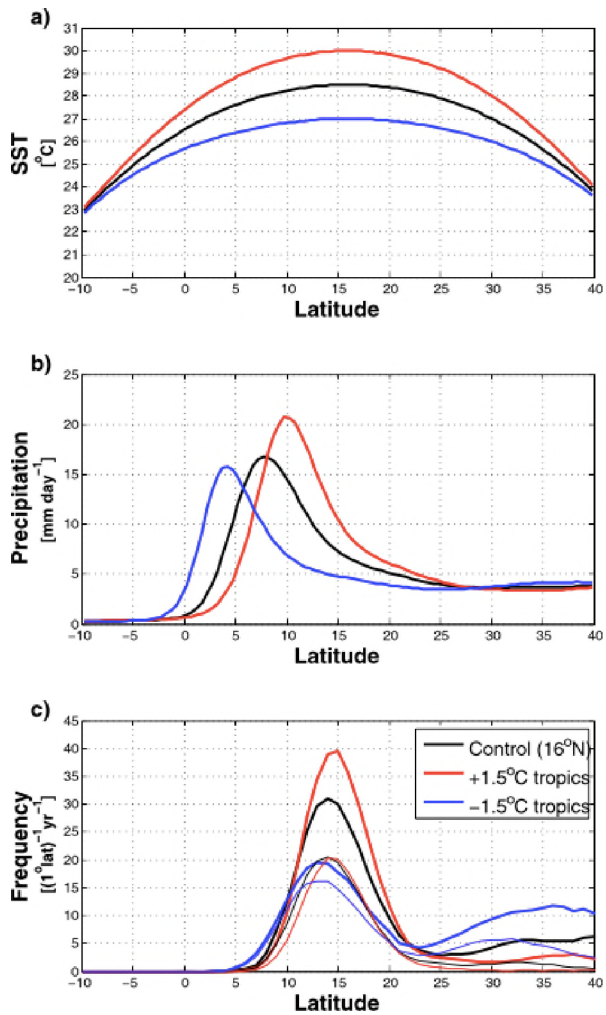

Figure 1: (a) Prescribed sea surface temperatures, (b) precipitation rate, and (c)frequency of tropical storm genesis as a function of latitude in 3 aquaplanet simulations, from Ballinger et al (2015). Thick lines in (c) show all tropical storms while thin lines show stronger hurricane-strength storms. With increasing SSTs, precipitation moves poleward, storm genesis increases, while the ratio of strong storms to all storms (a measure of intensity) decreases.

1c) Spherical rotating radiative-convective equilibrium

As a bridge between the homogeneous rotating RCE studies and the aquaplanet simulations discussed above Merlis et al (2016) has simplified the aquaplanet simulations so that they are forced homogeneously, with uniform prescribed SSTs and with uniform solar forcing. The only source of horizontal inhomogeneity is provided by the rotating sphere. There are no extratropical storms in this geometry to distort TC genesis. The preferred region of TC genesis is found to be the subtropics, but moves polewards and the genesis frequency decreases with increasing SST, while the average intensity increases. Poleward vortex drift prevents accumulation of TCs in the subtropics, but long-lived storms accumulate in high latitudes. These results provide yet more input challenging our theories for the spatial structure and frequency of TC genesis. Because the polewafd drift keeps the subtropics from becoming densely packed with storms, it provides a more realistic gemoetry for studying how the genesis rates depend on the model's sub-grid closures and resolution in future work.

(2) Self-aggregating deep convection

In models of radiative-convective equilibrium it is known that convection can spontaneously aggregate into one single localized moist region if the domain is large enough. The large changes in the mean climate state and radiative fluxes accompanying this self-aggregation raise questions as to what simulations at lower resolutions with parameterized convection, in similar homogeneous geometries, should be expected to produce to be considered successful in mimicking a cloud-resolving model. With Caroline Muller, we investigate this self-aggregation in a non-rotating, three-dimensional cloud-resolving model on a square domain without large-scale forcing. We find that self-aggregation is not only sensitive to the domain size, but also to the horizontal resolution. With horizontally homogeneous initial conditions, convective aggregation only occurs on domains larger than 200 km and with resolutions coarser than 2 km in the model examined. The system exhibits hysteresis, so that with aggregated initial conditions, convection remains aggregated even at our finest resolution, 500 m, as long as the domain is greater than 200-300 km. The sensitivity of self-aggregation to resolution and domain size in this model is due to the sensitivity of the distribution of low clouds to these two parameters. Indeed, the mechanism responsible for the aggregation of convection is the dynamical response to the longwave radiative cooling from low clouds. Strong longwave cooling near cloud top in dry regions forces downward motion, which by continuity generates inflow near cloud top and near-surface outflow from dry regions. This circulation results in the net export of moist static energy from regions with low moist static energy, yielding a positive feedback. These results were published in Muller and Held (2012),.

This topic is of growing interest in that changes in convective aggregation with increasing temperature could alter climate sensitivity in ways not currently captured in GCMs. It is also potentially relevant to the initiation of tropical cyclones when large-scale forcing is weak, as exemplified by the rotating radiative-convective equilibrium configuration described above. Because of the complexity of this aggregation process, and its sensitivity to resolution and domain scale, we have not yet been able to use RCE to evaluate convective parameterizations systematically, as previously envisioned. These difficulties are described in the Zhou's Ph. D. thesis.

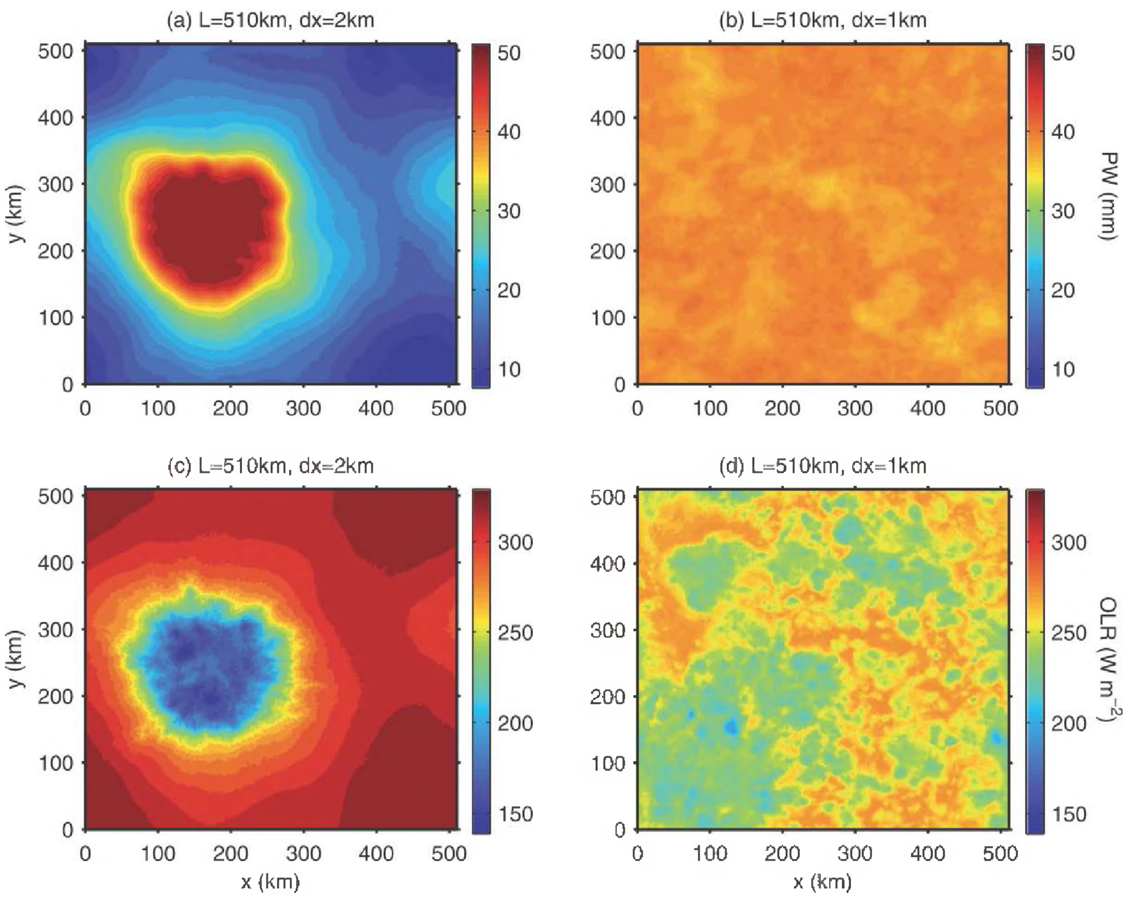

Figure21: Daily mean (a),(b) precipitable water (PW) and (c),(d) outgoing longwave radiation (OLR) after 60 days in two simulations with the same domain size but different resolutions (as indicated in figures). Self-aggregation is observed in the run with lower resolution (panels a, c), resulting in a moist region where convection is concentrated, surrounded by air with very dry conditions and strong longwave cooling. Similar effects may be obtained by changing the domain size.
[Muller and Held, 2012]

(3) Tropical wave dynamics

Vertically propagating waves in the tropics play an important role for stratospheric dynamics and as such can also have an impact on the extratropical circulation. In order to better understand the vertical propagation of equatorial Kelvin waves, specifically their transition from convectively coupled waves in the troposphere to free traveling waves in the stratosphere, Co-Investigator Fueglistaler and Graduate Student Tom Flannaghan developed a new filtering technique in the space/time domain that allows the separation of wave activity into number of waves and wave amplitude [Flannaghan and Fueglistaler, 2012]. The phase speed of Kelvin waves (order 20m/s) is similar to the magnitude of zonal wind in the tropical tropopause layer (TTL), and we find that the seasonal and interannual variability of Kelvin wave propagation is dominated by the variability in the wind field, and less by tropospheric convectively coupled wave activity [Flannaghan and Fueglistaler, 2013]. We also show that local relations between wave activity and zonal wind are ambiguous, and only full ray tracing calculations can explain the observed patterns of wave activity. Easterlies amplify and deflect the eastward traveling waves upwards. Westerlies have the opposite effect. During boreal winter, the strong dipole of zonal winds in the TTL centered at the dateline confines wave propagation into the stratosphere to a window over the Atlantic-Indian Ocean sector (30W to 90E), which casts a lasting "shadow" into the lower stratosphere that explains the remarkable zonal asymmetry in wave activity there (see Figure 2, taken from Flannaghan and Fueglistaler, 2013). During boreal summer, the upper level Monsoon circulation leads to maximum Easterlies, and wave amplitude (but not number of waves) maximizes over the Indian ocean sector (30E to 90E). Interannual variability in wave propagation due to El-Nino/Southern Oscillation, for example, is well explained by its modification of the zonal wind field.

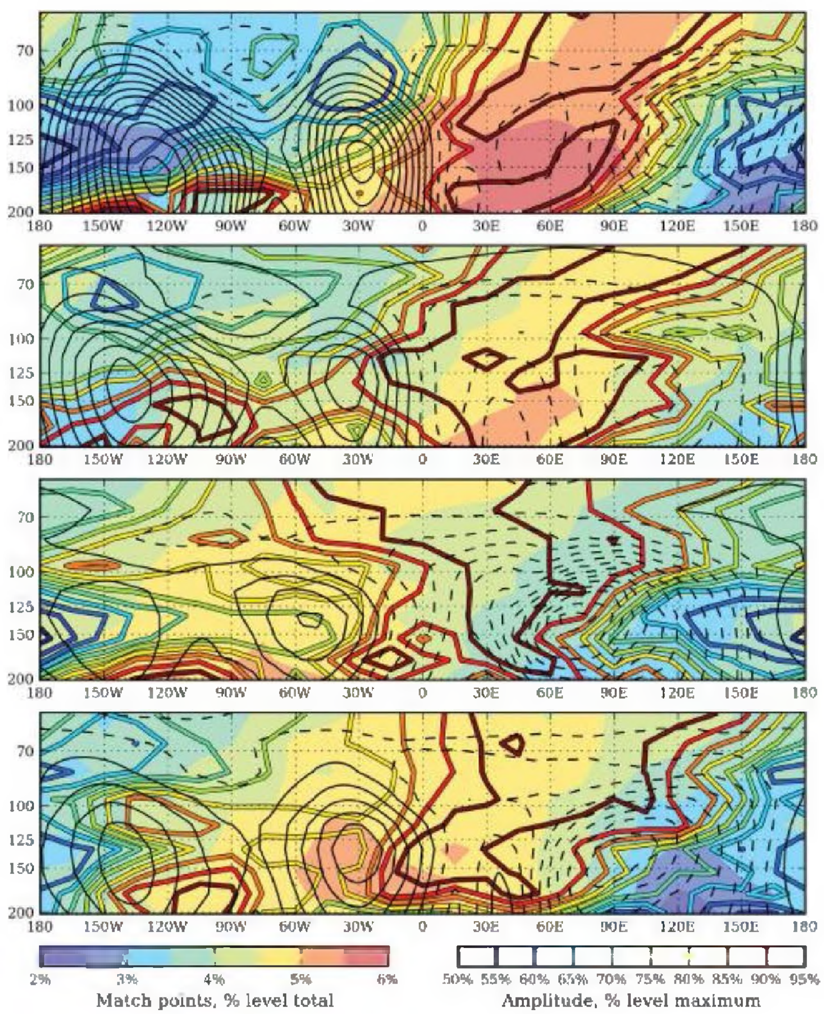

Figure 2: Statistics computed from the set of all waves tracked through the TTL from 202 hPa to 65 hPa during (a) DJF, (b) MAM, (c) JJA, and (d) SON. The colored shading shows the number of these waves which pass through each location, as a fraction of the total number of match points in such waves on each level. The colored contours show average amplitude of these waves at each location, normalized by the layer maximum. The black contours show the time-averaged zonal velocity with a contour spacing of 2m/s (dashed contours are negative (easterlies)).
[Flannaghan and Fueglistaler, 2013]

(4) Tropical warming and sea surface temperature trends

A robust result from climate models is that the tropical upper troposphere will warm more than the surface in response to increasing CO_2 concentrations, but the observational evidence for this pattern has been repeatedly challenged. In a project led by PI Held and Co-I Fueglistaler, we addressed the problem from a hitherto unexplored angle. Since free-running climate models cannot exactly reproduce the ocean heat uptake variations over the past ~3 decades, detailed comparison of the vertical structure of the atmospheric temperature trends between models and observations requires prescribed sea surface temperatures for the climate model runs. In Flannaghan et al. [2014] we show that rather subtle uncertainties in sea surface temperature data used as boundary conditions for the climate model runs submitted to the IPCC AR5 archive prevent strong conclusions concerning the vertical structure of temperature trends since the late 1970's. Specifically, we show that the General Circulation Models' atmospheric temperature trends in the upper troposphere very strongly depend on the sea surface temperature trends in the warmest percentiles. This result is consistent with our understanding of the atmosphere – deep convection occurs preferentially over the warmest waters – but the two widely used sea surface temperature data sets HadISST and Hurrell SST (recommended for AR5) differ most significantly in their trends over the warmest waters (see Figure 3).

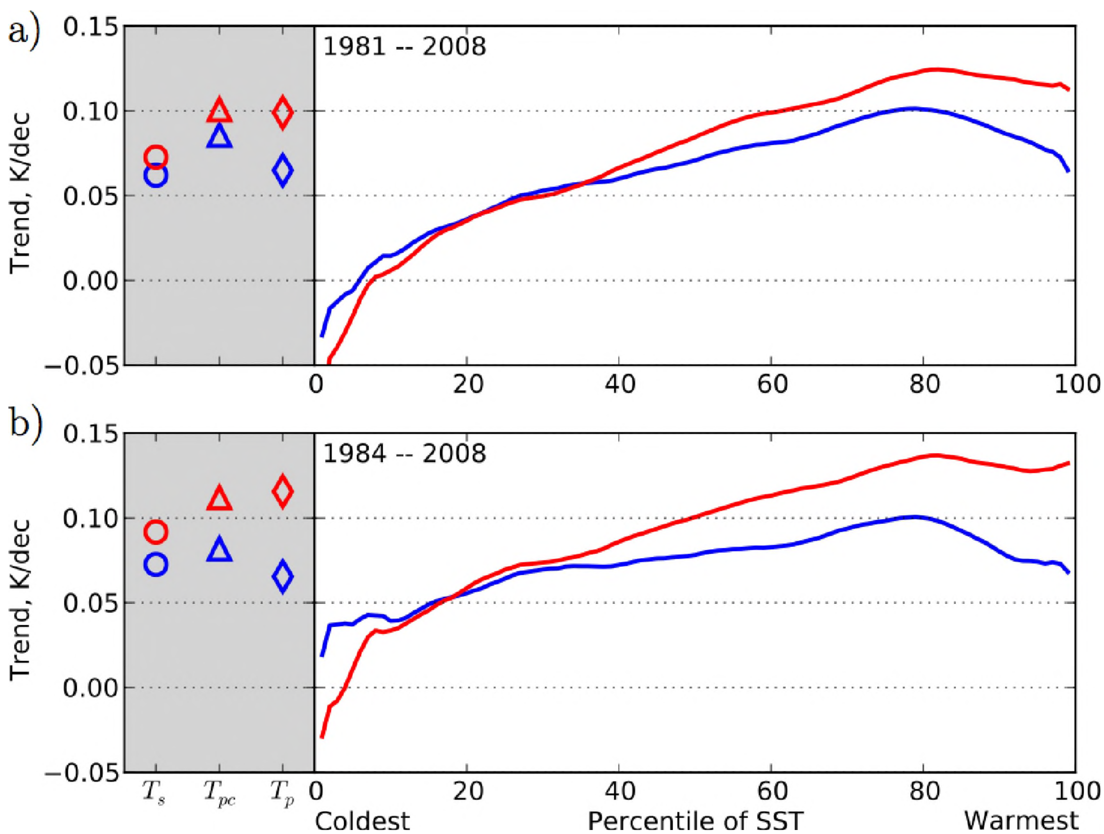

Figure 3: Trends of the percentiles of tropical SST in the HadISST1 (blue) and Hurrell (red) data sets over (a) 1981–2008 and (b) 1984–2008. The symbols show the trend in average SST (circles), SST weighted with the climatological precipitation (triangles), and the precipitation-weighted SST (diamonds). The black filled symbols show the difference between the Hurrell-based and HadISST1-based calculations. Figure from Flannaghan et al. [2014].

In Fueglistaler et al. [2015] we further show that a model's response in the geographic distribution of deep convection to changes in sea surface temperature patterns is an important factor for understanding why different general circulation models produce different upper tropospheric temperature trends even when forced with identical sea surface temperatures.

(5) Stratospheric water trends

Water entering the stratosphere is strongly constrained by the temperatures around the exceptionally cold tropical tropopause, but the exact processes controlling this "last dehydration" remain incompletely understood. In order to understand processes better and identify possible problems and biases in models, observational data must be compared to model data that has the best possible reconstruction of circulation and temperature for the period and location of the observations. Correspondingly, we have used meteorological reanalysis data for this project led by Co-I Fueglistaler, rather than a free running general circulation model. Specifically, we use trajectory calculations based on reanalysis data to address the question to what extent the large scale circulation and temperatures can explain observations of stratospheric water. We conclude that these two factors indeed are key, but that some interesting residuals remain even when considering uncertainties in temperature (compare the model results (in color) to the observations (black) of panel b).

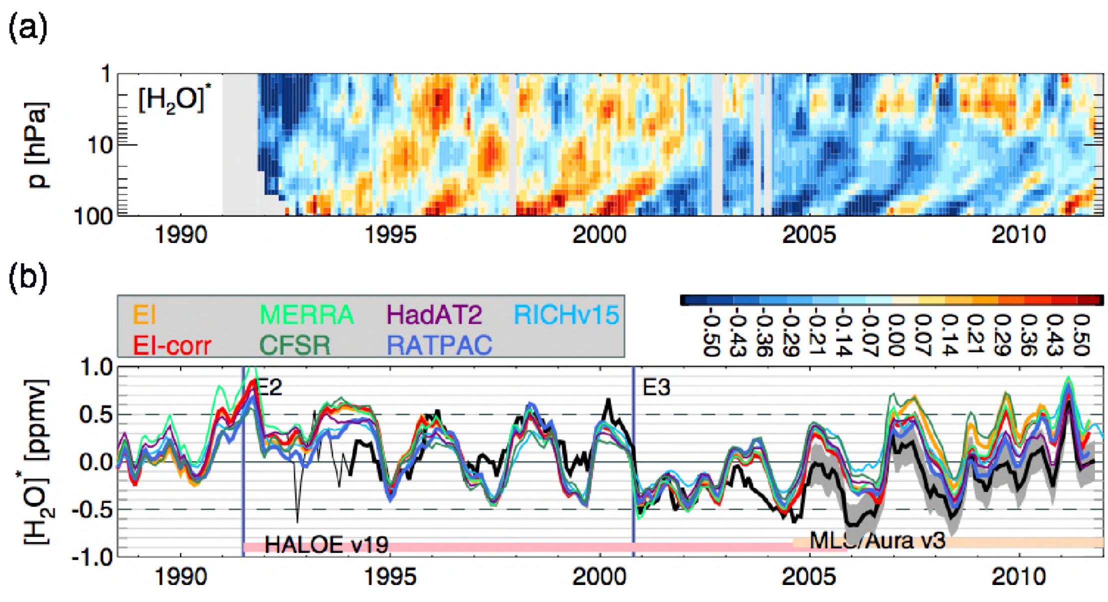

Figure 4: (a) Interannual variability of tropical (25S-25N) water vapor (H2O*, color coded, in ppmv) from HALOE (up to 2005) and MLS (from 2005 onward), with MLS adjusted. (b) H2O* from HALOE and MLS (as in Panel a) at 82 hPa (black line); HALOE interpolated linearly in log-pressure. Dark gray for MLS is 1 std. deviation uncertainty in the merging of HALOE and MLS. Lagrangian model estimates (color code shown in Figure) based on ERA-Interim, ERA-Interim corrected, and with

temperatures corrected based on the quasi-stationary temperature Field of MERRA and CFSR, and tropical means for homogenized radiosonde data. Figure from Fueglistaler et al. [2013].

The last dehydration prior to entering the stratosphere often occurs in thin cirrus clouds that require very high resolution in particular in the vertical in numerical models that is not feasible for global-scale models. In Dinh and Fueglistaler [2014] we use a model configuration with very high resolution in the vertical, but with highly idealized large-scale structure in 2-dimensions only. This model configuration allows to assess the dehydration efficiency of thin ice clouds rather accurately, and we find that these clouds actually dehydrate air fairly efficiently (efficiency in this context means that the resulting water vapor mixing ratio is close to the minimum saturation mixing ratio encountered by an air mass).

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