TRMM data show a super-Clausius Clapeyron sensitivity in heavy rain in a warmer climate

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The water holding capacity of the Earth's atmosphere is governed by the Clausius-Clapeyron (CC) Law which states that there is approximately a 7% increase in atmospheric water vapor per degree rise in temperature. It has been an ongoing debate in the scientific community whether or not rainfall should be increasing at the CC rate as a result of global warming.

In a recent paper, Lau and Wu (2011) address the above question by examining oceanic rainfall distribution ranked by rain rates, using TMI (microwave) and PR (radar) rainfall data from the Tropical Rainfall Measuring Mission (TRMM) for the period 1998-2009. The geographic locations of light, moderate, and heavy rains (Fig.1), defined by the bottom 5% (B5), the inter-quartile range (I25) and the top 10% (T10), indicate that moderate and heavy rains are confined to SST warmer than 27^{o} C. The joint probability distributions with cloud top temperature and radar-echo-top height (Fig. 2) show that B5 rain is primarily associated with warm, low cloud, I25 with mixed-phase precipitation, middle to high clouds, and T10 with high clouds and ice-phase precipitation. Both TMI and PR (Fig. 3) show that heavy rains (>50-70 percentile) have a super-CC sensitivity with extreme heavy rains (top 5%) exhibiting 80-90% increase per degree rise in SST. In contrast, light and moderate rains which account for 30-50% of the tropical rainfall amount show a reverse CC sensitivity, with 5-10% reduction per degree rise. The differences are related to changes in large-scale dynamics and tropical convection.

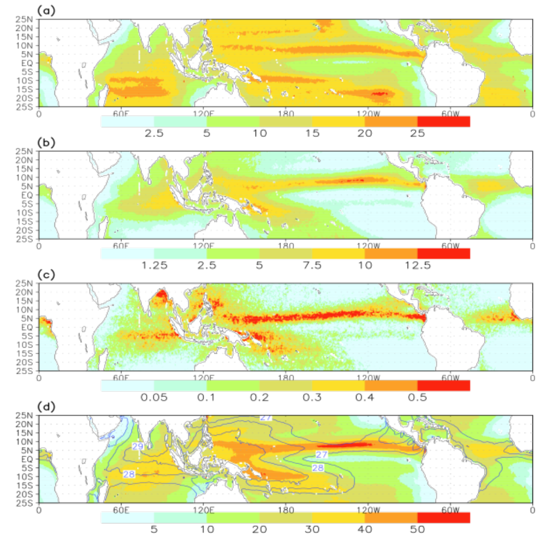

Figure 1: Geographic distribution of rain occurrence of each rain category based on TRMM Microwave Imager (TMI) data for (a) light rain (B5), (b) intermediate rain (I25), (c) heavy rain (T10), and (d) total rain (all rain types), in percentage frequency of occurrence. Superimposed on (d) is sea surface temperature in contour lines of 27, 28, and 29 °C.

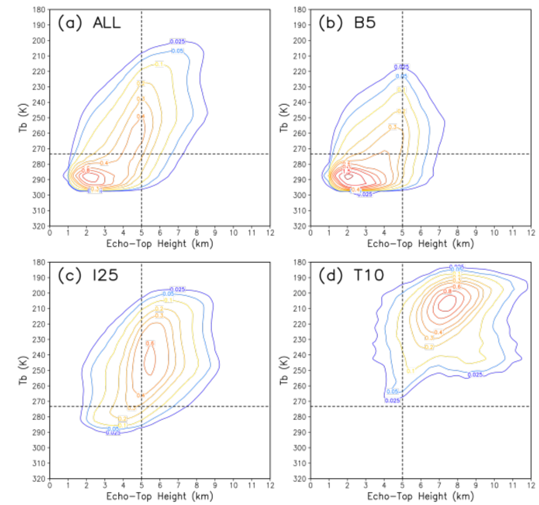

Figure 2: Joint probability distribution functions of TRMM Precipitation Radar (PR) echo-top height and Visible and Infrared Scanner (VIRS) channel-4 brightness temperature (Tb) based on daily data for tropical oceanic (a) total (all rain types), (b) B5, (c) I25, and (d) T10 rains.

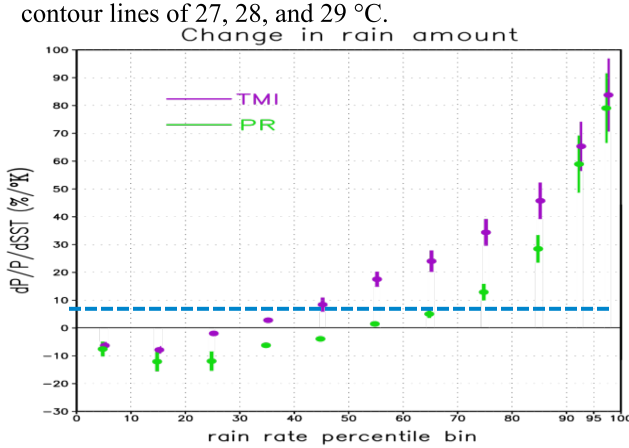

Figure 3: Changes in annual rain amount per degree K sea surface temperature rise calculated from linear regressions by rain category (classified by contributed rain amount percentile) from TMI and PR data, respectively. Linear fits with significant (> 95%) confidence levels are noted with their corresponding $\pm$1.96 standard deviation marked by vertical bar. The 7% CC sensitivity is indicated by the bold (blue) dashed line.

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References:

Lau, K.-M., and H.-T. Wu , 2011: Climatology and changes in tropical oceanic rainfall characteristics inferred from Tropical Rainfall Measuring Mission (TRMM) data (1998–2009), *Journal of Geophysical Research*, 116, D17111, doi:10.1029/2011JD015827.
Lau, K. M., and H. T. Wu, 2007: Trends in tropical rainfall characteristic, 1979-2003. *International. Journal of Climatology,* 27, 979-988, doi:10.1002/joc. 1454.

Data Sources: TRMM Science Data and Information System; The Hadley Center monthly SST.

Technical Description of Figures:

Figure 1: Light (bottom 5%, B5) rain events dominate the rain occurrence and are found over the large expanses of tropical and subtropical oceans. Intermediate (25^{th} to 75^{th} percentile, I25) rain events occur mostly over the warm pool regions and account for the major rain amount contribution. The tight spatial gradient for heavy rain (top 10%, T10) is consistent with the close connection between organized deep convection and large-scale dynamics, in addition to the control of warm pool.

Figure 2: Light rain events are associated with low and warm cloud tops. Intermediate rain dominate the rain occurrence and are found over the large expanses of tropical and subtropical oceans. Intermediate rain is contributed by a wide range of middle and mixed-phase rain. The top 10% heavy rain occupies a regime of cold cloud tops and elevated echo top heights, predominantly associated with deep convection and ice phase ice phase precipitation.

Figure 3: This image shows the sensitivity of the rate of change in rain amount of different rain types to the change in tropical mean SST. Based on their contributed rain amount, the daily rain events for the period from 1998 through 2009 have been separated into 11 categories (with bin 1 being the lightest rain, and bin 11, the heaviest). The percentage change of rain amount of different rain types (bins) to SST changes (dP/P/dSST), or rainfall sensitivity is then computed based on linear regression of the slope of the changes as a function of SST for each rain bin. Both TMI (in purple) and PR (in green) analyses indicate positive rainfall sensitivity for moderate-heavy to very-heavy rain (the last 6 bins), and negative sensitivity for light-to-moderate rain (the first 3 bins). Except for the transition zone around the 20–40 percentile rain rate (bins 3 and 4) for TMI and 30–60 percentile (bins 4–6) for PR, all calculated rainfall sensitivities are significant to the 95% confidence levels. Note that rain amount of the most extreme rain events (bin 11, top 5% in contributed rain amount) is nearly double (80 to 90 % increase) per degree SST increase.

Scientific significance: This research represents a best effort approach to use a variety of TRMM products to study climate change. Results show that even a chronological trend in total rainfall is absent in the relatively short term TRMM data record (12 years), useful information regarding possible changes in rainfall characteristics with respect to sea surface temperature (SST) may be inferred from TRMM data. We find that rainfall sensitivity to tropical mean SST is strongly dependent on rain types. Heavy rains are highly sensitive to temperature, with 80-90% increase per degree rise in SST, while light and moderate rains show negative sensitivity with 5-10% reduction per degree SST rise. Many climate scientists believe that precipitation is governed by the same theoretical Clausius Clapeyron (CC) relationship for water vapor and temperature, implying that there is approximately a 7% increase in precipitation per degree rise in temperature. However, our results indicate that because of large-scale dynamics feedback for different types of rainfall, the CC relationship is not an appropriate constraint for precipitation changes in a warmer climate.

Relevance for future science and relationship to Decadal Survey: This research would serve as a benchmark for future extended analyses into the Global Precipitation Measurement (GPM) mission timeframe. The GPM mission will further expand the rainfall products to a global domain with improved sampling and detection for mid-latitude rain systems, including solid precipitation.

First Full Tropospheric Wind Profiles Obtained with the TWiLiTE Doppler Lidar

Bruce Gentry (Code 612, GSFC), Huailin Chen (612, SSAI), Jaime Cervantes (612, SSAI)

Observation of the wind field plays an important role in understanding the dynamics of the atmosphere at all scales, global and mesoscale. The NRC Earth Science Decadal Survey has recommended a Global 3D Wind Mission to meet this observational need from space. In addition, wind sensing instruments flying on high altitude aircraft can fill an important gap in observing critical smaller scale process like hurricane genesis and intensification. The Tropospheric Wind Lidar Technology Experiment (TWiLiTE) is a Doppler lidar system that measures vertical profiles of wind in clear air by measuring the Doppler shift of laser signal scattered back to the instrument by molecules.

- TWiLiTE is the first airborne Doppler lidar system of this type and demonstrates many of the key technologies needed to enable the Global 3D Wind mission.

- Recent engineering flights on NASA's ER-2 aircraft demonstrated the autonomous operational capabilities of the instrument.

- Science flights of TWiLiTE produced the first full tropospheric (0-20 km altitude) lidar wind profiles from an airborne platform.

Figure 1: TWiLiTE lidar in the ER-2 QBay

Figure 2: Flight track from the Feb 15, 2011 ER2 test flight from Palmdale CA to Denver, CO.

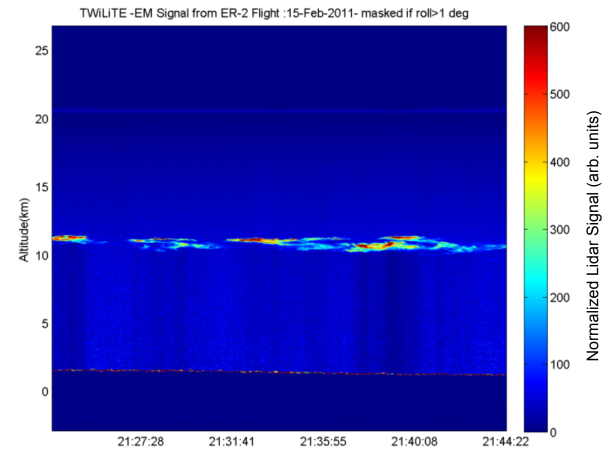

Figure 3: A 15-minute time series of normalized lidar backscatter signals from the Feb 15, 2011 ER2 test flight taken over Denver, CO. Note cirrus layer at 11 km and ground return at ~ 1.6 km

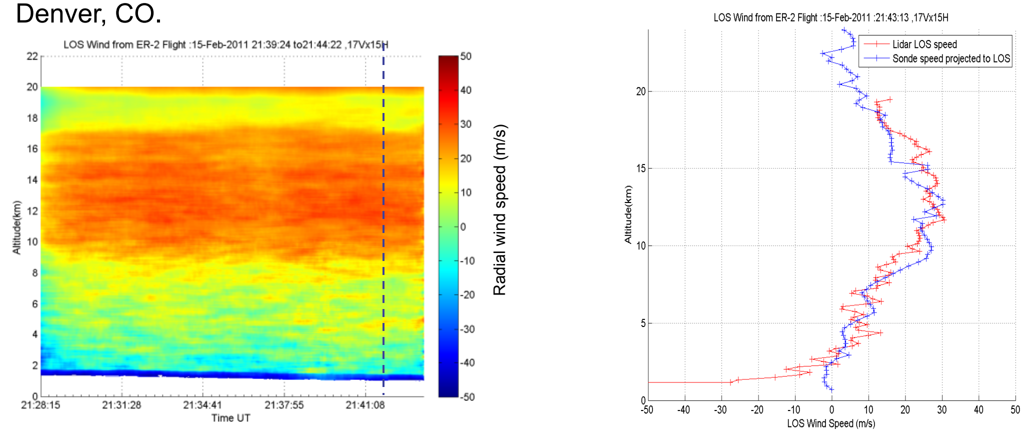

Figure 4 : Left: A 15-minute time series of TWiLiTE radial wind profiles from the Feb 15, 2011 test flight taken while the ER-2 was flying over Denver, CO. Right : A single TWiLiTE profile (red) compared with wind profile data from the National Weather Service radiosonde (blue) launched from Denver, CO approximately 3 hours after the lidar data were taken (00Z, Feb16).

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1) "Recent US Activities Toward Development of a Global Tropospheric 3D Wind Profiling System" , Gentry, B., R. Atlas , W. Baker, G.D. Emmitt, R.M. Hardesty, R. Kakar, M. Kavaya, S. Mango, K. Miller, L.P. Riishojgaard, *Proceedings of the American Geophysical Union Fall Meeting*, San Francisco, CA, December, 2008.
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Technical Description of Figures:
Figure 1: The TWiLiTE instrument installed in the ER-2 Q_Bay.
Figure 2: Flight track from the Feb 15, 2011 ER2 test flight from Palmdale CA to Denver, CO. Approximately 4 hours of lidar wind data were obtained during this 5.5 hour flight along with a wealth of engineering data that will help in understanding and improving the operation of the instrument.
Figure 3: A 15-minute time series of range normalized lidar backscatter signal profiles from the Feb 15, 2011 ER2 test flight taken while the aircraft was over Denver, CO. The ER2 is flying at an altitude of 20.7 km. The lidar is pointing at a nadir angle of 45 deg. and the data have a 1 second (~200 m) along track resolution and a range resolution of 30 m (21 m vertical). Note the cirrus layer at 11 km and ground return at ~ 1.6 km. The lidar penetrates the optically thin cirrus and can still measure winds at lower altitudes (see figure 4). Thicker clouds will attenuate the signals further.
Figure 4: Time series of TWiLiTE radial wind profiles from Feb 15, 2011 ER2 test flight. A 15-minute segment of lidar winds taken over Denver, CO is shown on the left. The temporal averaging of the lidar wind profiles is 11 seconds and the vertical resolution is 252 m. On the right, a single TWiLiTE wind profile (red) is compared with wind profile data from the National Weather Service radiosonde (blue) launched from Denver, CO, approximately 3 hours after the lidar data were taken (00Z, Feb16). For this comparison, the radiosonde wind speed and direction has been used to calculate a radial wind speed projected to the azimuth direction of the laser.

Scientific significance: The TWiLiTE Doppler lidar flying on high altitude aircraft such as the NASA ER-2 or Global Hawk provides a unique capability to study the dynamics of atmospheric processes including hurricane genesis and intensification. Full tropospheric (0 to 20 km altitude) profiles of horizontal wind are derived from TWiLiTE in clear air over the long duration of an ER-2 (6 hours) or Global Hawk (30 hours) flight. This is a new capability currently filled neither by satellites or manned aircraft.

Relevance for future science and relationship to Decadal Survey :
The National Research Council Decadal Survey for Earth Science identifies a Global Tropospheric 3-D Wind mission as one of the 15 priority missions recommended. The panel's first recommended step is for NASA to develop and aircraft test the lidar technology, followed by a pre-operational space mission to demonstrate the measurement concept and establish the performance standards for an operational wind mission. TWiLiTE project advances the technology readiness level of the key technologies of a molecular direct detection wind lidar system on the roadmap to the Global 3D Winds Mission.

Acknowledgement: The TWiLiTE instrument was developed under the NASA ESTO Instrument Incubator Program with additional support from the Airborne Instrument Technology Transition program

First Ultraviolet Reflectivity Measurements of Diurnal Variations of Clouds

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Quantifying the amount of clouds as a function of time of day is important for climate models and radiation budget estimates.

32 years of NASA & NOAA satellite measurements have been assembled into 5 degree zonal means and analyzed to produce these results. The instruments were designed to measure ozone in the UltraViolet part of the spectrum (340 nm) and can also be used to measure clouds.

The zonal mean reflectivity amount is directly related to cloudiness, and thus a quantification of energy reflected back into space as a function of time of day. 1 Reflectivity Unit = 1% reflection back into space.

Cloud amounts from this study agree with the results from the MODIS instruments on Terra & Aqua.

Future measurements of diurnal changes in cloud amount will be made from the NASA/ NOAA DSCOVR mission satellite to be located at Lagrange 1. This satellite is currently scheduled for launch in Jan, 2014.

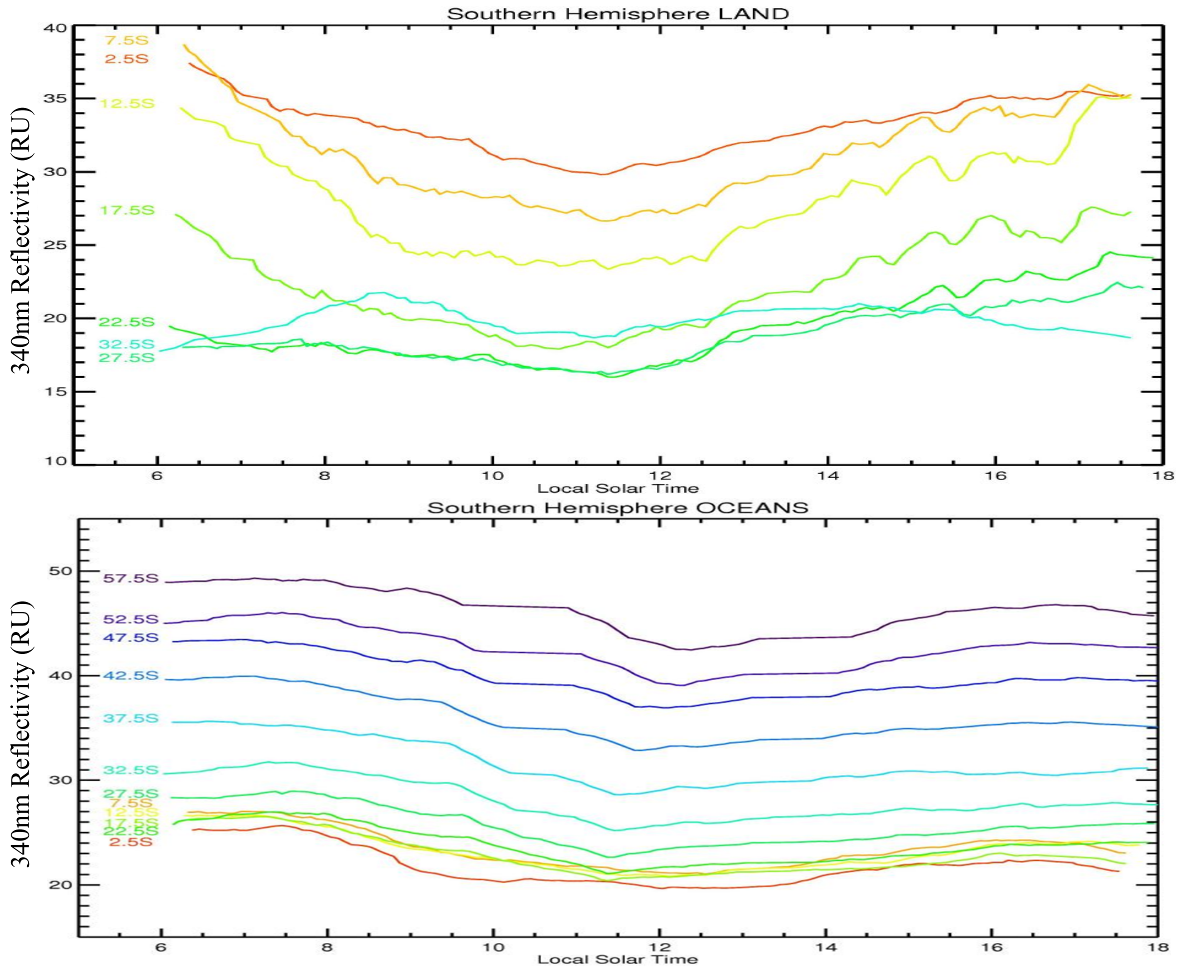

Figure 1 top: Changes in cloudiness for 5 degree zonal means over land for the Southern Hemisphere as a function of time of day. It is more cloudy in the morning in the equatorial zones (due to jungles) than in the sub tropics. The afternoon gets significantly more cloudy due to convection. **Figure 1 bottom:** Shows that over water it is slightly more cloudy in the morning than in the afternoon.

Earth Sciences - Atmospheres

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Labow, G. J., J. R. Herman, L. Huang, S. A. Lloyd, M. T. DeLand, W. Qin, J. Mao, and D. E. Larko (2011), Diurnal variation of 340 nm Lambertian equivalent reflectivity due to clouds and aerosols over land and oceans, *J. Geophys. Res.*, 116, D11202, doi:10.1029/2010JD014980.

Data Sources: 340 Nanometer reflectivity data are taken from Nimbus-7 Solar Backscatter UltraViolet (SBUV) instrument, NOAA-9, NOAA-11, NOAA14, NOAA-16, NOAA-17, NOAA-18 SBUV/2 and AURA's Ozone Monitoring Instrument (OMI)

Technical Description of Figure: Figure 1 shows that it is significantly more cloudy over land in the equatorial zones than in the southern sub tropics. The 5 degree zone from the Equator to 5 South reflects roughly 35% of the light back into space compared to the 25-30 South zone which reflects less than 20%. Conversely, over water the equatorial band is very similar to the sub tropic bands and the amount of cloudiness increases rapidly as one moves further south to the mid latitudes. The figure also shows the change in cloudiness as a function of time of day. On land it is more cloudy in the morning in the equatorial zones (due to jungles) than in the sub tropics. The afternoon gets significantly more cloudy due to convection. Over water it is slightly more cloudy in the morning than in the afternoon.

Scientific significance: Meteorological observations are consistent with these findings, and show that over water at low latitudes there is a persistent boundary layer of mist and fog in the morning due to high relative humidity from low air temperatures and high dew point temperatures from ocean spray. Towards noon, as the air temperature rises, the low level mist and fog decreases as the relative humidity decreases, resulting in the lower reflectivity values. In the late afternoon and evening, as the air temperatures continue to rise, afternoon convection leading to widespread cumulus and cumulonimbus cloud production results in the higher reflectivity values. A similar effect can be seen in the land measurements due to high early morning dew points over predominantly jungle vegetation, particularly over the Amazon region of South America. At the middle latitudes over land, the air tends to be dry and the reflectivities in the morning and towards noon tend to be low with generally clearer skies and lower dew points Towards late afternoon and evening, as the land heats up and air temperatures rise, cumulus convection produces more clouds which result in the higher reflectivity values seen over land. A similar clearing effect to that over the water is seen towards noon as the air temperature rises. In the late afternoon significantly more cumulus convection occurs over land than over the oceans.

This work can be used to quantify the amount of energy reflected back into space due to clouds and aerosols as a function of time of day. I.E. there are 25% more clouds at 7a.m. than at noon for the zone containing land for 10-15 degrees south. These data can be put into global climate and energy balance models.

Relevance for future science and relationship to Decadal Survey:

Once the diurnal changes in cloud cover have been measured, long-term, global cloud trends can be calculated from this data set and global heating and/or cooling rates can be inferred. Future missions such as ACE (Aerosol/Cloud/Ecosystem) and DSCOVR (Deep Space Climate Observatory) will study clouds with much more accuracy than currently possible.