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LETTER

How is the relationship between rainfall and water vapor in the Indian monsoon influenced by changes in lapse rate during global warming?

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Abstract

Most climate models have shown that the Indian Summer Monsoon Rainfall (ISMR) will increase on account of global warming. The primary reason is the increase in column water vapor (CWV). The rainfall increase is not, however, proportional to the increase in column water vapor; for a given amount of CWV, rainfall will be lower in the future, according to model simulations. This suggests that other there are factors are at play. We have used a diagnostic model based on moist static energy (MSE) and moisture conservation to examine the impact of changes in the vertical lapse rate of temperature. Our results indicate that on decadal time scales, changes in ISMR are mediated by changes in CWV and temperature lapse rates. This is consistent with previous studies that showed the impact of column-mean temperature on the rainfall-CWV relationship. Findings are significant for climate model projections of ISMR, as correct estimation of lapse rate changes in models is necessary to predict ISMR changes accurately.

1. Introduction

In tropical oceans, there is a non-linear relationship between rainfall and column water vapor (Bretherton *et al* 2004). The nonlinearity is because more than one factor controls rainfall over a region, even though water vapor is the dominant one. Rushley *et al* (2018) reexamined this relationship and looked at model biases concerning this relationship. Additionally, Neelin *et al* (2022) reviewed this relationship in the context of extreme rainfall. The explicit exponential relationship obtained in previous studies has also been used as a constraint in numerical model simulations (Daleu *et al* 2016). This relationship between rainfall and water vapor has not been examined over monsoonal regions.

The water vapor content in the atmosphere depends on its temperature. According to the Clausius–Clapeyron equation - it increases by about 7% per unit increase in temperature in current climate conditions. Although there are regional differences, it has been shown that climate models closely follow this relationship (O'Gorman and Muller 2010). We also expect the rainfall variability locally and globally to increase because of the warming (Menon *et al* 2013, Pendergrass *et al* 2017, Katzenberger *et al* 2021), especially over land. On top of the increased variability, there is a robust increase in seasonal mean rainfall (Bengtsson 2010). Climate models show that this increase in mean rainfall is strongly linked to the increased column water vapor (Held and Soden 2006, Lee *et al* 2018, Akinsanola *et al* 2020).

Precipitation does not increase linearly with column water vapor, and previous studies that diagnosed the causes for this mainly focused on global mean precipitation (Allen and Ingram 2002, Held and Soden 2006, Vecchi and Soden 2007). Global mean precipitation increases are only around 2%–3% per unit increase in temperature, and this is attributed to the weakening large-scale circulation. However, Chou and Neelin (2004) showed that the regional impacts of warming on precipitation are mediated by feedbacks and mechanisms quite different from global precipitation response, but they did not precisely concentrate on specific regions; hence, simple arguments based on the moisture budget (e.g., Held and Soden 2006) might not be suitable to examine the impacts of warming on monsoonal precipitation.

It is often argued that precipitation changes arise from thermodynamic changes (increase in moisture) and are offset regionally or globally by dynamic changes (decrease in convective mass flux or vertical velocity) (e.g., Held and Soden 2006, Vecchi and Soden 2007, Sooraj *et al* 2015). Such a separation is artificial, as Neelin *et al* (2022) state: *'This can be severely misleading since dynamic changes arise from the need to satisfy thermodynamic balances.'* A better physical insight can be obtained by looking at both moisture and moist static energy (MSE) budgets simultaneously (Neelin and Held 1987).

Neelin and Held (1987) developed a model for tropical convergence by combining moisture and MSE conservation. This has several advantages, the most prominent being its simplicity and diagnostic uses. This framework begins with the integral forms of the conservation equations for a single column of the atmosphere in pressure coordinates (see equations (1) and (2)). The time derivatives are not considered, assuming a steady state. The contributions of the horizontal gradients of temperature and moisture to the overall energy and moisture budgets are then neglected. This is a reasonable approximation for the tropics.

$$\langle \nabla \cdot \mathrm{m}\vec{\mathrm{U}} \rangle + \left\langle \frac{\partial \mathrm{m}\omega}{\partial \mathrm{p}} \right\rangle = F_B - F_T \tag{1}$$

$$\langle \nabla \cdot \mathrm{q}\vec{\mathrm{U}} \rangle + \left\langle \frac{\partial \mathrm{q}\omega}{\partial \mathrm{p}} \right\rangle = E - P \tag{2}$$

where,

U = Horizontal velocity
ω = Vertical velocity
P = Precipitation
E = Evaporation
F_B = Radiative, sensible, and evaporative heat fluxes at the surface
F_T = Radiative fluxes at the top of the atmosphere
m = Moist Static Energy (MSE)
q = Specific humidity
$\langle\rangle$ represents vertical integral

Following this, Srinivasan (2001) further developed another model for seasonal mean monsoon precipitation and explored the relationship between rainfall and water vapor over land. This framework has been used in the past to explain the impact of the earth's precession on tropical precipitation (Jalihal *et al* 2019), variations in rainfall due to global warming (Chou and Neelin 2004, Chou *et al* 2006), the response of tropical precipitation to aerosols (Chou *et al* 2005), and how forest cover changes influence monsoon rainfall (Samuel *et al* 2023). In this paper, we examine how the relationship between monsoon rainfall and water vapor changes on account of global warming.

2. Data and methods

We have used the predictions from 12 climate models (models chosen are given in the supplementary material) that participated in the coupled model intercomparison project (CMIP6) (Eyring *et al* 2016). For the period 1850–2014, we chose the historical simulation as it is supposed to represent the past climate accurately. For the future simulation, we have used the ssp585 scenario (previously RCP 8.5), which has the highest CO2 forcing of all the simulations (Kriegler *et al* 2017). The 12 models were picked based on their ability to reproduce the mean and seasonal cycle of the Indian monsoon, as indicated by Rajendran *et al* (2022).

We have used the monthly mean data from ERA5 reanalysis made available by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Hersbach *et al* 2020). ERA5 has an impressive resolution of $0.25^\circ \times 0.25^\circ$ and has good temporal coverage. For calculations done over land regions, we averaged over land points only for the Indian region (10–30N, 70–90E).

For diagnosis, we have used the thermodynamic monsoon model developed by Srinivasan (2001). This model uses the moist static energy budget framework by Neelin and Held (1987). Based on this model, seasonal mean precipitation over the tropics can be expressed as:

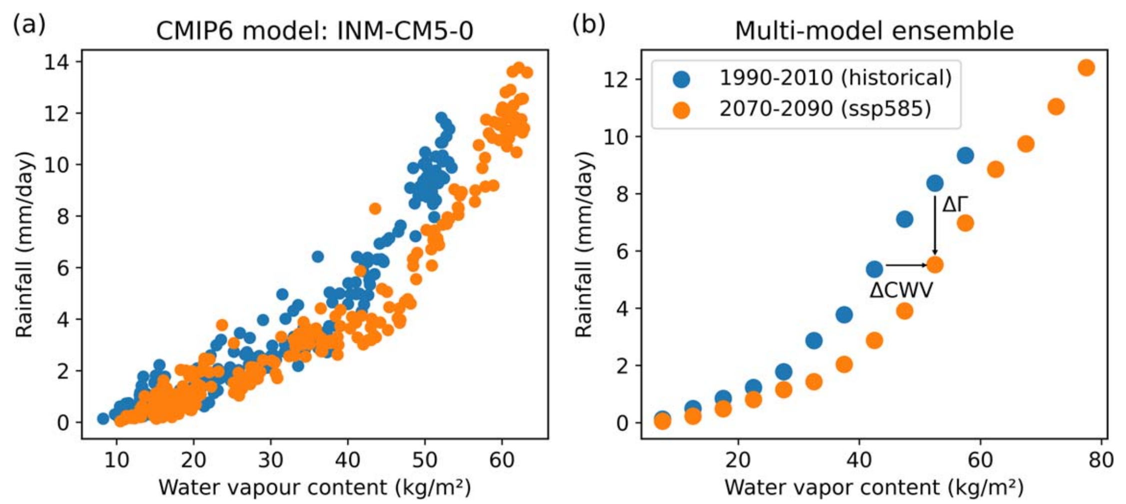

Figure 1. (a) Spatially averaged rainfall as a function of column water vapor (CWV), for the model INM-CM5–0. The region is the Indian subcontinent (10–30N, 70–90E), and each point in the plot represents the average number for one month from a particular year in the chosen period. (b) As in figure 1(a), but each curve here is now the ensemble average of the chosen 12 CMIP6 models, by binning the data into bins of CWV.

$$P = E + \frac{Qnet}{\frac{C}{CWV} - 1} \tag{3}$$

Here, P is precipitation (rainfall), E is evaporation, Qnet is net downward radiative fluxes at the top of the atmosphere, CWV is column water vapor, and C is a parameter. Following equations (1) and (2), the model further assumes that the tropospheric lapse rate is constant with height and neglects energy storage on land (i.e., F_B from equation (1) is neglected). All assumptions made by the model work well for mean climatic conditions, especially on longer timescales, thus suitable for our application.

3. Results

3.1. Results from CMIP6

In figure 1(a), the monthly averaged rainfall has been plotted against column water vapor (CWV) for two 20-year periods for all months, using data from one model. We observe a rightward shift of the curve, which is seen across all models, as evidenced by figure 1(b). Note that for a given amount of column water vapor, the rainfall in the future will be less than that at present. The nonlinearity of the relationship is similar to that we see over the oceans (Bretherton *et al* 2004).

In order to understand the reason for this, we look at each of the parameters that precipitation depends on from equation (3).

We find that the parameter C has an increasing trend, especially after the year 2000, when global warming started increasing rapidly. To see why this is the case, we need to know what the parameter depends on. The parameter C depends upon the temperature and moisture profiles of the atmosphere and the surface temperature. (see Srinivasan 2001 for details). Specifically, the variables that control C are Γ, λ, and T_0, where:

$\lambda =$ Water vapor scale height (non-dimensional)

$\Gamma =$ Tropospheric lapse rate of temperature

$T_0 =$ Surface temperature

The lapse rate (Γ) plays the most prominent role in controlling this parameter. On a decadal timescale, the lapse rate is decreasing (see figure 2), consistent with previous studies. This further contributes to a decrease in λ. A decreasing λ indicates that the upper atmosphere is becoming moist at a faster rate than the lower atmosphere. This makes sense since the decreasing lapse rate makes the upper troposphere warmer. Moreover, the change in T_0 by a few degrees cannot explain the huge change in the parameter C. Fitting the parameter C as a function of lapse rate using a linear function, we get our new model for tropical precipitation, which is more relevant in the context of climate change:

$$\boldsymbol{P = E + \frac{Qnet}{\frac{C_0 - \beta\Gamma}{CWV} - 1}} \tag{4}$$

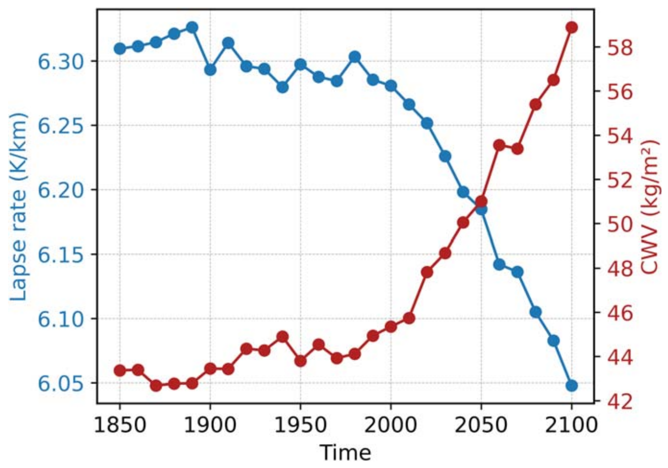

Figure 2. Increase in CWV and decrease in lapse rate (Γ) due to warming of the atmosphere in INM-CM5–0 over the Indian land region.

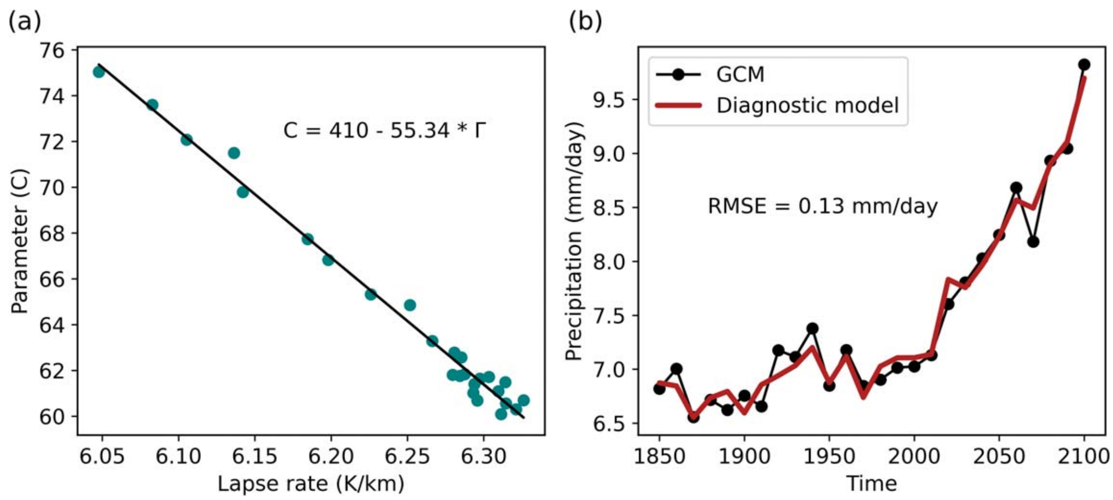

Figure 3. (a) Parameter C from equation (3) as a linear function of lapse rate in INM-CM5–0. (b) Decadal precipitation as predicted by the new model in comparison with model output data. The root mean squared error is 0.13 mm day^{-1}.

In figure 3, the rainfall predictions using this new model are compared with the CMIP6 model rainfall. The model works remarkably well on a decadal time scale with a root mean square error of less than 0.5 mm day^{-1}. This highlights the critical role the lapse rate plays in ISMR under global warming; hence, ISMR changes are controlled mainly by changes in CWV and lapse rates.

3.2. Results from present climate

The curve shifting towards the right can also be observed in the present climate, albeit less prominent (see figure 4). Even though modest, binning monthly rainfall into bins of CWV shows that there is a difference between the rainfall-water vapor curves between the first and last decades of available data from ERA5 reanalysis. The fact that we could see this separation in reanalysis data is impressive because of the modest amount of warming during this period. In essence, this separation is clear evidence of a warming climate.

4. Summary and discussion

We have demonstrated that the relationship between the Indian summer monsoon rainfall and water vapor is changing due to global warming. This change manifests itself as a rightward shift of the rainfall-water vapor curve. This also implies that deep convection or precipitation pickup will happen at a higher CWV in the future. Furthermore, we have shown that this change is due to two main factors: the changes in the vertical stratification

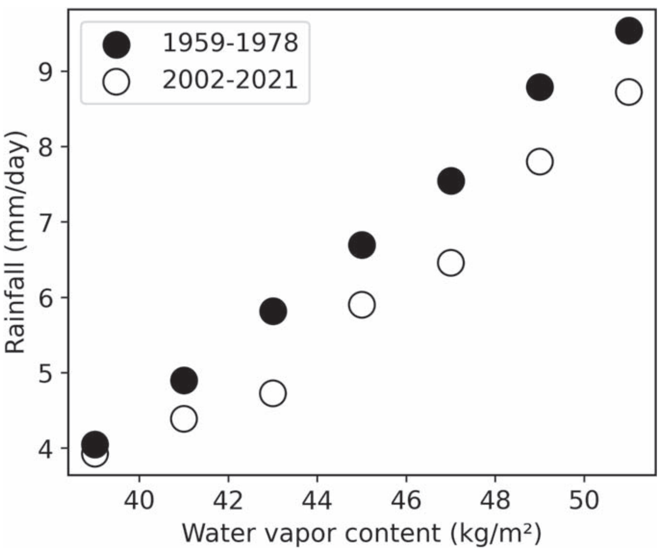

Figure 4. Spatially averaged rainfall as a function of column water vapor (CWV) for JJAS months only, binned and averaged for the given periods. Data is from ERA5 reanalysis.

of the atmosphere, specifically, the decreasing lapse rate, and changes in column water vapor. The upper troposphere is warming up at a faster rate compared to the lower troposphere.

Neelin *et al* (2009) showed that the rainfall-water vapor relationship over a region depends on the average temperature of the atmospheric column above it or the column-mean temperature. Our results are consistent with theirs since the column-mean air temperature is increasing as a consequence of decreasing lapse rate. Hence, the two approaches are equivalent. This study might be thought of as an extension of their work since we show that the temperature profile of the atmosphere also matters, not just the mean temperature. The decreasing lapse rate, as Santer *et al* (2005) point out, is a natural consequence of warming since a colder lower troposphere will be less buoyant and hence more stable, and is a robust feature of all climate model simulations (Fu *et al* 2011). In the future, as more moist air parcels are lifted and condensed (due to increased rainfall and water vapor), latent heat release in the upper troposphere will also increase, which contributes to the increase in the upper troposphere warming.

The density of moist parcels of air is a function of their humidity and temperature, both of which are increasing in the atmosphere. For such parcels to be lifted from ground level, their density must be lower than the column, up to the height at which condensation happens. But, because the upper troposphere is warming up more rapidly, the density of air is decreasing more rapidly in the upper troposphere because moist air is less dense than dry air. This means it takes higher density differences to lift parcels. Hence, these parcels must have higher water vapor content to have enough buoyancy to lift and condense, leading to rainfall. This is why, for a given amount of water vapor, the rainfall will be lower in the future compared to the present.

A weakening circulation contributes to precipitation changes, but vertical velocity changes are a consequence of the weakening vertical temperature gradient that initiates the feedback (see Neelin *et al* 2022 for a discussion on how dynamic changes arise from changes in the thermodynamic environment). This is true even for zonal and meridional circulation changes (see Ma *et al* 2012).

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Data availability statement

Data available at https://esgf-node.llnl.gov/search/cmip6/ and https://esgf-index1.ceda.ac.uk/search/cmip6-ceda/. Please contact the authors if you encounter any problems with the links. The data that support the findings of this study are available upon reasonable request from the authors. https://doi.org/https://esgf-node.llnl.gov/search/cmip6/.

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References

Akinsanola A A, Zhou W, Zhou T and Keenlyside N 2020 Amplification of synoptic to annual variability of West African summer monsoon rainfall under global warming *Npj. Climate and Atmospheric Science* **3** 21
Allen M R and Ingram W J 2002 Constraints on future changes in climate and the hydrologic cycle *Nature* **419** 224–32
Bengtsson L 2010 The global atmospheric water cycle *Environ. Res. Lett.* **5** 025202
Bretherton C S, Peters M E and Back L E 2004 Relationships between water vapor path and precipitation over the tropical oceans *J. Clim.* **17** 1517–28
Chou C and Neelin J D 2004 Mechanisms of global warming impacts on regional tropical precipitation *J. Clim.* **17** 2688–701
Chou C, Neelin J D, Lohmann U and Feichter J 2005 Local and remote impacts of aerosol climate forcing on tropical precipitation *J. Clim.* **18** 4621–36
Chou C, Neelin J D, Tu J-Y and Chen C-T 2006 Regional tropical precipitation change mechanisms in ECHAM4/OPYC3 under global warming *J. Clim.* **19** 4207–23
Daleu C L *et al* 2016 Intercomparison of methods of coupling between convection and large-scale circulation: 2. Comparison over nonuniform surface conditions *Journal of Advances in Modeling Earth Systems* **8** 387–405
Eyring V, Bony S, Meehl G A, Senior C A, Stevens B, Stouffer R J and Taylor K E 2016 Overview of the coupled model intercomparison project phase 6 (CMIP6) experimental design and organization *Geoscientific Model Development* **9** 1937–58
Fu Q, Manabe S and Johanson C M 2011 On the warming in the tropical upper troposphere: Models versus observations *Geophys. Res. Lett.* **38** L15704
Held I M and Soden B J 2006 Robust responses of the hydrological cycle to global warming *J. Clim.* **19** 5686–99
Hersbach H *et al* 2020 The ERA5 global reanalysis *Q. J. R. Meteorolog. Soc.* **146** 1999–2049
Jalihal C, Bosmans J H C, Srinivasan J and Chakraborty A 2019 The response of tropical precipitation to earth's precession: the role of energy fluxes and vertical stability *Climate of the Past* **15** 449–62
Katzenberger A, Schewe J, Pongratz J and Levermann A 2021 Robust increase of indian monsoon rainfall and its variability under future warming in CMIP6 models *Earth System Dynamics* **12** 367–86
Kriegler E *et al* 2017 Fossil-fueled development (SSP5): An energy and resource intensive scenario for the 21st century *Global Environ. Change* **42** 297–315
Lee D, Min S-K, Fischer E, Shiogama H, Bethke I, Lierhammer L and Scinocca J F 2018 Impacts of half a degree additional warming on the asian summer monsoon rainfall characteristics *Environ. Res. Lett.* **13** 044033
Ma J, Xie S-P and Kosaka Y 2012 Mechanisms for tropical tropospheric circulation change in response to global warming *J. Clim.* **25** 2979–94
Menon A, Levermann A and Schewe J 2013 Enhanced future variability during India's rainy season *Geophys. Res. Lett.* **40** 3242–7
Neelin J D and Held I M 1987 Modeling tropical convergence based on the moist static energy budget *Mon. Weather Rev.* **115** 3–12
Neelin J D, Martinez-Villalobos C, Stechmann S N, Ahmed F, Chen G, Norris J M, Kuo Y-H and Lenderink G 2022 Precipitation extremes and water vapor *Current Climate Change Reports* **8** 17–33
Neelin J D, Peters O and Hales K 2009 The transition to strong convection *J. Atmos. Sci.* **66** 2367–84
O'Gorman P A and Muller C J 2010 How closely do changes in surface and column water vapor follow clausius–clapeyron scaling in climate change simulations? *Environ. Res. Lett.* **5** 025207
Pendergrass A G, Knutti R, Lehner F, Deser C and Sanderson B M 2017 Precipitation variability increases in a warmer climate *Sci. Rep.* **7** 17966
Rajendran K, Surendran S, Varghese S J and Sathyanath A 2022 Simulation of Indian summer monsoon rainfall, interannual variability and teleconnections: evaluation of CMIP6 models *Clim. Dyn.* **58** 2693–723
Rushley S S, Kim D, Bretherton C S and Ahn M-S 2018 Reexamining the nonlinear moisture-precipitation relationship over the tropical oceans *Geophys. Res. Lett.* **45** 1133–40
Samuel J B, Chakraborty A and Paleri A 2023 Deciphering the relationship between vegetation and indian summer monsoon rainfall *Environ. Res. Lett.* **18** 044023
Santer B D *et al* 2005 Amplification of surface temperature trends and variability in the tropical atmosphere *Science* **309** 1551–6
Sooraj K P, Terray P and Mujumdar M 2015 Global warming and the weakening of the asian summer monsoon circulation: assessments from the CMIP5 models *Clim. Dyn.* **45** 233–52
Srinivasan J 2001 A simple thermodynamic model for seasonal variation of monsoon rainfall *Curr. Sci.* **80** 73–7
Vecchi G A and Soden B J 2007 Global warming and the weakening of the tropical circulation *J. Clim.* **20** 4316–40