Orographic control of Cold Pool precipitation during Indian Summer Monsoon Season

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Introduction

- India receives 80% of the annual rainfall during the summer monsoon season: June-July-August-September.
- Although there exists a spatial variability in the intensity of seasonal mean rainfall over India and its surroundings, most of the domain experiences rainfall higher than 6 mm/day (Fig.1a).
- One such spatial variability feature is the low rainfall over Southern Bay of Bengal along east coast of Indian peninsula (termed as Cold Pool, in this study) during summer monsoon season.
- Cold Pool receives rainfall less than 2 mm/day.

The Mystery of the Bay of Bengal Cold Pool

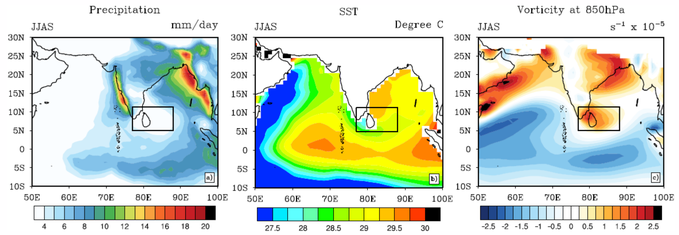


FIG. 1. The climatology of a) JJAS precipitation (TRMM), b) sea surface temperature (OISST-v2) and, c) 850 hPa vorticity (MERRA) during Indian Summer Monsoon season. The area inside the box is the Cold Pool.

Fig 1b: Sea Surface Temperature is well above the critical temperature (27.5°C) (Gadgil et al. (1984)) for triggering the convection over the Bay.
Fig 1c: Positive vorticity above boundary layer (850 hPa).
Fig 1a: Still no rainfall!!!!

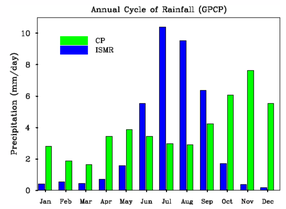


FIG. 2. Annual cycle of precipitation over Indian land mass (blue) and Cold Pool (green).
- Cold Pool exhibits a very different annual cycle of precipitation compared to that over Indian landmass.
- There are two peaks in the annual cycle for Cold Pool, one in May (4 mm/day) and the other in November (8 mm/day).
- This is unlike in the case of all India monsoon, which has only one major peak in July (10 mm/day).

What do the observations show?

- Cold Pool is situated near the south-east of the Western Ghat Mountains (WG).
- During summer monsoon, the rain carrying westerlies hit the mountains and precipitate along the windward side of the WG.
- The rain holding air after ascending and precipitating over the mountain slopes, reaches the top, descent adiabatically over the mountain slopes, becomes dry and warm by the time it stretches the foot of the mountains.

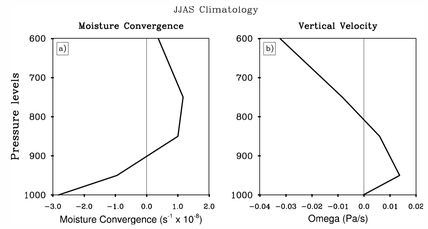


FIG 3. The vertical structure of vertical velocity and moisture convergence.
- They show divergence near surface and descent below 800 hPa over Cold Pool.
- So, the existence of Cold Pool could be associated with the presence of WG.

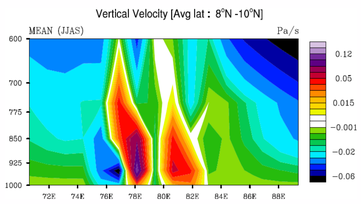


FIG 4. The vertical section of the vertical velocities averaged over 8N to 10N, shows clear bands of positive and negative vertical velocities are adjacent to each other like a wave.
- There is a wave pattern of ascent and descent.
- The Cold Pool is in a region of descent

Are these waves related to Western Ghat orography?
We conducted AGCMs experiments to understand this.

Is there any association between the precipitation over Cold Pool and the Western Ghat Mountains???

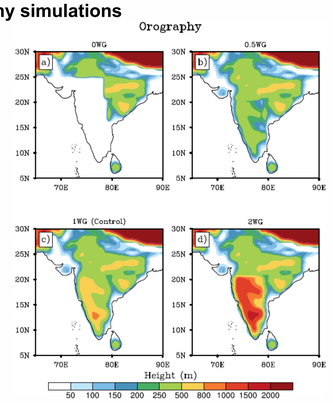
Details of the Global Forecasting System (GFS) Model used for this study

Horizontal Resolution	Triangular truncation at 190 waves (0.62°x0.62°)
Vertical Resolution	64 unequally spaced hybrid sigma levels
Time Step	6 minutes
Convection	Relaxed Arakawa and Schubert (Moorthi and Suarez, 1992)
Land Surface Process	NOAH Land Surface Model
Orography	Mean orography from USGS - DEM
Sea Surface Temperature	Monthly climatology of Optimum Interpolation (OI)-SST interpolated to model time step (Reynolds and Smith (1994)).

Details of perturbed orography simulations

Name	Description
0WG	No Western Ghats : Orography is removed from 10° - 16° N and 79° - 85° E.
0.5WG	The height of Western Ghats is reduced by half of its original value.
1WG	Simulation with mean orography.
2WG	The height of Western Ghats is doubled.

FIG. 5. Model orography over India for the four different cases in the increasing order of the height of WG (from top left corner to bottom right).



Did the variation in orography change the distribution of rainfall over Indian monsoon region?

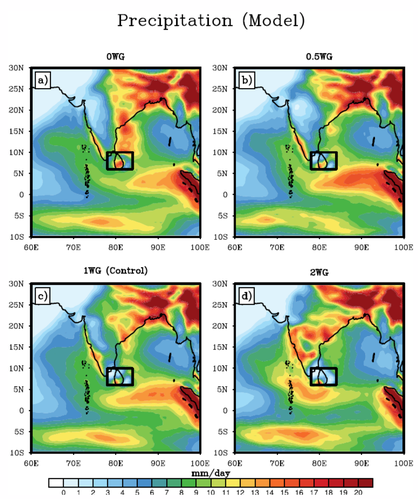
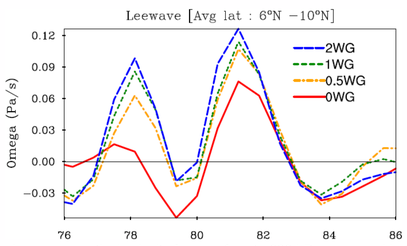


FIG. 6. Climatology of JJAS precipitation for the four different cases a) 0WG, b) 0.5WG, c) 1WG and d) 2WG. 1WG is the control run which has the mean orography. The area inside the box is the Cold Pool.
- Spatial distribution of rainfall over the Indian monsoon region is changing with change in height of WG.
- Rainfall over Cold pool is also changing with the change in height of WG.

Did it modify the strength of the lee waves?



YES!!!

FIG. 7. Vertically integrated pressure vertical velocity from surface to 600 hPa, averaged between 6°N to 10°N.
- Increase in strength of lee waves with the increase in height of WG.

How does the increase in strength of lee waves modify JJAS rainfall over Cold Pool?

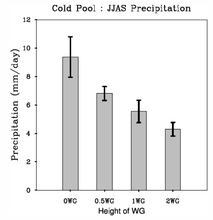


FIG. 8. The mean JJAS precipitation over Cold Pool with the increase in height of WG.
JJAS precipitation reduces linearly when the height of WG changes from 0 to double the height of WG.

How does the rainfall increase with decrease in height of WG?

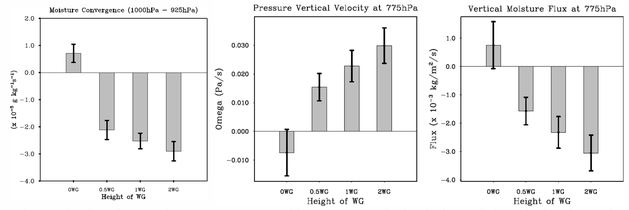
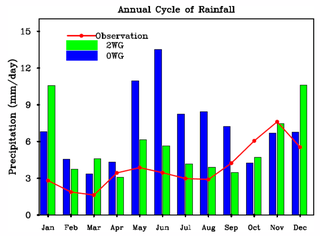


FIG. 9. The change in a) surface moisture convergence, b) pressure vertical velocity and c) vertical moisture flux above the boundary layer with the increase in height of WG.
With the decrease in height of the WG,
- There is an increase in moisture convergence in the boundary layer.
- There is decrease in descend in the column.
- There is an increase in moisture flux above boundary layer.
- There is a transition from unfavorable to favourable conditions for convection from 0.5WG to 0WG in all the above figures. => **The presence or absence of WG has very important role in changing precipitation over Cold Pool.**

Did it modify the annual cycle of precipitation over Cold Pool?



YES!!!

FIG. 10. Comparison of the annual cycle of rainfall over Cold Pool for 0WG and 2WG from the model with that for Cold Pool in observation (GPCP). The red dots are the values for the observation. For 0WG, the major peak comes in June.
- In 0WG simulations, the annual cycle of rainfall over Cold Pool shows a primary peak during June (similar to that of all India rainfall) instead of November and a secondary peak during November-December.
- In the case of 2WG, the annual cycle of Cold Pool becomes very close to that of Cold Pool in observation with a very prominent peak in December.

Conclusions

Cold Pool is a situated in the southern part of the peninsular India, which receives very less rainfall during summer monsoon season, compared to its surrounding regions, even though the conditions for convection and precipitation are favourable.

- We found that, **Inhibition of convection that prevails over Cold Pool is provided by WG through lee waves.**
- With the increase in height of WG, the strength of these waves increases providing more and more descent over Cold Pool.

- **Once the WG are removed, these waves disappears:**
  Removing the descend over the region associated with these waves.
  Providing the moisture blocked by WG, by increasing the surface moisture convergence as well as the vertical flux above boundary layer.

- **There is an inverse relationship between the height of WG and precipitation over Cold Pool.**
- The precipitation changed from **9.3 mm/day to 4.1 mm/day** when we increased the height of the mountains from 0 to double the height of WG. **This is almost 56% reduction in precipitation**.

- The annual cycle of Cold Pool itself got modified by the removal of WG.
- **In the absence of WG, the annual cycle of precipitation over Cold Pool becomes more 'monsoon like' with a peak during June.**
  Therefore, WG orography plays a significant part in reduction of rainfall over Cold Pool.

The presence of Western Ghat Mountains play an instrumental role in the existence of Cold Pool.

References:
1. Gadgil et al, 1984: Nature, (312), 141–143.
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3. Moorthi, S., and M. J. Suarez, 1992: Monthly Weather Review, 120 (6), 978–1002.

Acknowledgment:
The authors thanks CTCZ - MoES for its support. Arushi P V thanks IISc and DCCC for travel support. Computations were conducted on DST-FIST supported cluster.