Slide 1: We know that Carbon is continuously cycled in the Earth system through a process called the global carbon cycle. The first picture here on the left-hand side presents The Global carbon cycle budget and its components. We see that approximately 30% of the Global emitted carbon dioxide is taken up by the terrestrial biosphere in the form of primary productivity.

Gross primary productivity (GPP) is the rate of CO_2 fixation by vegetation through photosynthesis. An increase in GPP signifies more and more anthropogenic emissions of CO_2 taken up by plants, and vice versa. There has been consensus on an increase in GPP in the last 30 to 40 years globally, with the changing climatic conditions and response to increasing atmospheric CO_2.

Slide 2: The Indian region is also vulnerable to a changing climate. There are changes observed in the rainfall, temperature, snow cover, etc., and as a result, we see sub-regional differences in these climatic parameters, for example, rainfall shown in the figure on the right. Changes in temperature and precipitation have direct implications for the biosphere.

Slide 3: There are changes observed in net primary productivity. We have studies suggesting there is an increase in primary productivity since 1980 over India as a response to the changing climate and increasing atmospheric CO_2. Most of these studies have taken NDVI as the proxy for vegetation.

Slide 4: Now, when the changes in met parameters have regional variations, also the ecosystem types are different from region to region, so in this study, we have first tried to understand the variability in gross primary productivity of different regions over India. We have selected four sample forest regions of India.

Data Used :

Study duration 2001-2019

Meteorological data

ERA-5 :

1.surface temperature (2m temperature)

2. rainfall flux in mm d^{-1}

3. soil moisture

4.Vapour Pressure Deficit (VPD)

F{surface pressure, temperature, specific humidity}

VPD = VP saturation - VP air

$$VPsat = \frac{610.7 \bullet 10^{(7.5T)/(237.3+T)}}{1000}$$

Vegetation Data

1. Gross Primary Productivity (GPP) : every 8-days carbon flux simulation from FLUXCOM (https://www.fluxcom.org/CFDownload/)

MODIS satellites vegetation indices:

2. NDVI : Normalised Difference Vegetation Index :16days frequency

3. EVI : Enhanced Vegetation Index :16-days frequency

4. LAI : Leaf Area Index - 8-days frequency , from july,2002 onwards

Vapour Pressure Deficit Calculation:

$$VPsat = \frac{610.7 \bullet 10^{(7.5T)/(237.3+T)}}{1000} \bullet \frac{RH}{100}$$

```
df = tairdf.astype(float)
es = pd.DataFrame()
es = 610.78 * 10**(7.5 *  df/ (237.3+df)) #gives in  pascal. divide
by 1000 to get  kPa
rh = qairdf/( 0.623 * es/(prdf-es))
ea = rh*es/100
vpd = es - ea
vpd = vpd/100 # converting in  hPa
```

Slide 5: Here, the climatic conditions at these locations are shown, such as an increase in temperature in summer months and rainfall following the Indian summer monsoon rainfall patterns. So is the VPD and soil water.
Slide 6: Then we see the biosphere characteristics like GPP and other vegetation indices, which suggest an increase in GPP and vegetation indices with an increase in GPP for the northeast region and the western ghats region in spring months.

Slide 7: Then we checked the trend of GPP at these locations, as seen that the NE had the highest increase, but the trend was highest for the WG region.

Supplementary table: GPP correlation with different vegetation indices in four seasons in India, suggesting seasonal fluctuations in GPP.

GPP correlation with Vegetation Indices

Region\Season	Winter (DJF)	Spring (MAM)	Summer (JJA)	Autumn (SON)
CI (EVI-GPP)	0.94	0.59	0.84*	0.91
(NDVI-GPP)	0.97	0.60	0.71	0.76
(LAI-GPP)	0.97	0.77	0.76	0.94
NE(EVI-GPP)	0.82	0.90*	0.69	0.72*
(NDVI-GPP)	0.82	0.76	0.67	0.43
(LAI-GPP)	0.84	0.84	0.81	0.64
WG (EVI-GPP)	0.82	0.86*	0.81	0.59
(NDVI-GPP)	0.91	0.57	0.81	0.55
(LAI-GPP)	0.57	0.49	0.87	0.77
WHNK(EVI-GPP)	0.35	0.88	0.86*	0.90
(NDVI-GPP)	0.18	0.74	0.77	0.83
(LAI-GPP)	0.62	0.91	0.82	0.95

All correlation 99% significant (p<0.01), except WHNK: NDVI-GPP (p=0.07)

Findings:

1. EVI is better correlated with GPP than the NDVI especially WHNK

Green colour: EVI stronger correlated to GPP than NDVI, for 11/16~70%

2. NDVI is good performer during winter seasons in3 regions except WHNK

3. LAI and GPP also show strong correlation (>=0.7) (12/16) in all seasons at all locations,

Blue colour: LAI strongest correlated to GPP for 9/16~56%

4. WG: Lai in winter & NDVI in spring is the highest

5.WHNK in winter is the only case of poor correlation, while others are strongly correlated in winter

Reference: Smrati Gupta, Pramit Kumar Deb Burman, Yogesh K. Tiwari, Umesh Chandra Dumka, Nikul Kumari, Ankur Srivastava, Akhilesh S. Raghubanshi, Understanding carbon sequestration trends using model and satellite data under different ecosystems in India,Science of The Total Environment, Volume 897,2023,166381, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2023.166381.

Slide 8: So these regional changes in the rate of GPP encouraged us further to study the long-term changes using climate model simulations for the country as a whole. For this, we used the CMIP6 coupled carbon feedback Earth system models from the historical to the future period available from 8 models (esm linked c4mip experiment). Analysing these models, we see an increase in the GPP during both historical and future projections. Historical 30 years show an increase in the rate of GPP and 2.3 grams of carbon per square metre per year. And the future projections in the SSP 585 suggest a 2.5-fold increase in all three periods of future projections, i.e., the early century, middle century, and the end of the century. It is around 6 grams of carbon per square metre per year, with the highest being in a middle Sanctuary at 6.09 gC m-2 y-2. Suggested GPP is to increase. So, are we happy about climate change? Not exactly…

Slide 9: Further analysing historical simulations, we have plotted the annual cycle of the GPP, which, following the monsoon rainfall, shows an increase in GPP in June-September, and then there is a decrease in the GPP during the winter.

Special distribution of the GPP in all the 8 models shows there is a high GPP in the Northeast region and along the Southwest part of India. The multimodal average also extends from Northwest India, shows a high GPP in the northeast, and the Southwest coast of India.

Data: CMIP6 Models C4MIP experiment, BGC models

8 Models (esm-historical + future: esm-ssp585 (Eyring et al., 2016)), all initializations

S. No.	Model Name	Institute	Atmosphere resolution	N2 cycle	Land Carbon and BGC	Reference
1	ACCESS-ESM1-5	CSIRO	1.25 x 1.875	Yes	CABLE2.4 with CASA CNP	Ziehn et al. (2020)
2	CNRM-ESM2-1	CNRM	1.4 x 1.4	No	ISBA-CTRIP	S´ef´erian et al. (2019)
3	CanESM5	CCCma	2.81 x 2.81	No	CLASS-CTEM	Swart et al. (2019)
4	GISS-E2-1-G-CC	NASA GISS	2 x 2.5			Kelley et al. (2020)
5	MIROC-ES2L	JAMSTEC	2.81 x 2.81	Yes	MATSIRO VISIT-e	Hajima et al. (2019)
6	MRI-ESM2-0	MRI	1.00 × 0.50	No	HAL	Yukimoto et al (2019)
7	NorESM2-LM	NCC	1.9 x 2.5	Yes	CLM5	Seland et al. (2020)
8	UKESM1-0-LL	UK	1.875 x 1.25	Yes	JULES-ES-1.0	Sellar et al., (2019)

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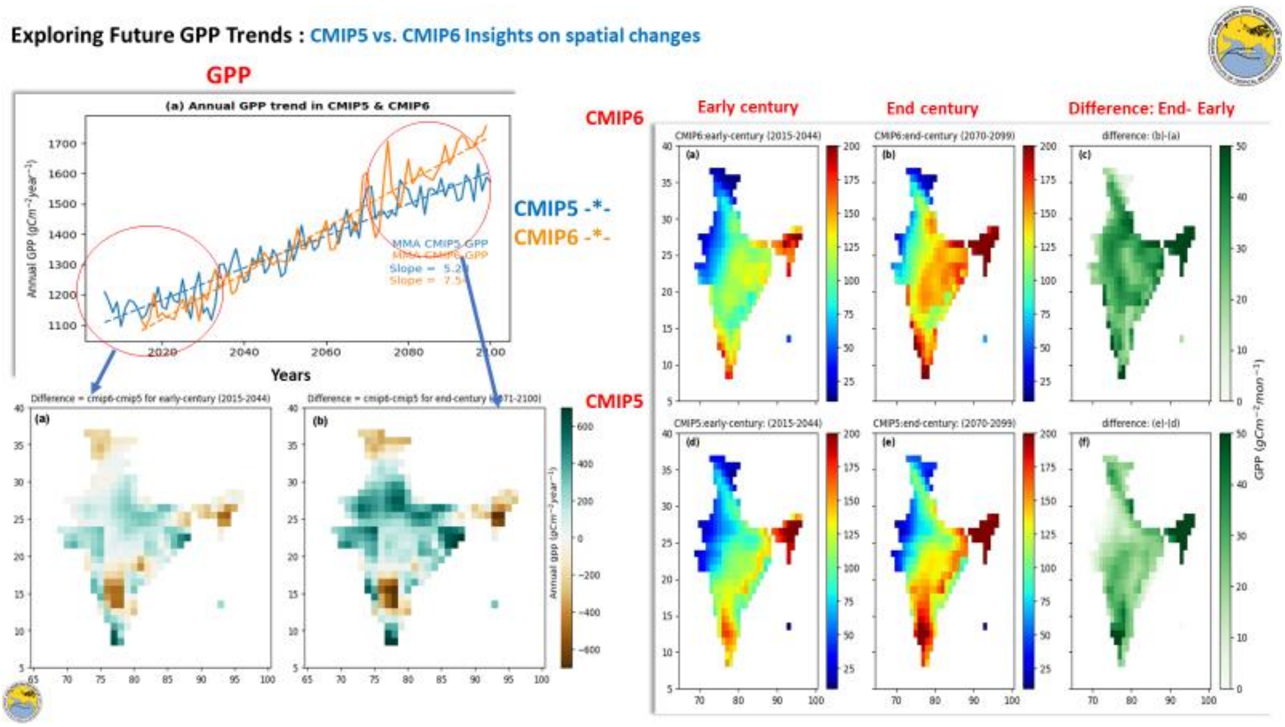
Slide 10: Forest and agriculture are the major contributors to regional GPP in the Indian region. Published data from the Forest Survey of India and land use statistics suggest there was an increase in the forest cover in the last decade and gross area under crop in the last three decades. Though there is an overall increase in forest and crop cover over India. Models are essentially replicating the well-forested regions in India. But we also checked the spatial changes from these reports; we see there is a decrease in the Northeast region and the Southwest coast, which shows a decrease in the forest and crop also in these regions. So it suggests that CMIP models are not able to capture this special variation in the land use changes that have been happening over India in the last few decades due to the prescribed land cover maps in the experiment design. So, what could be the reason for the increase in GPP in models?

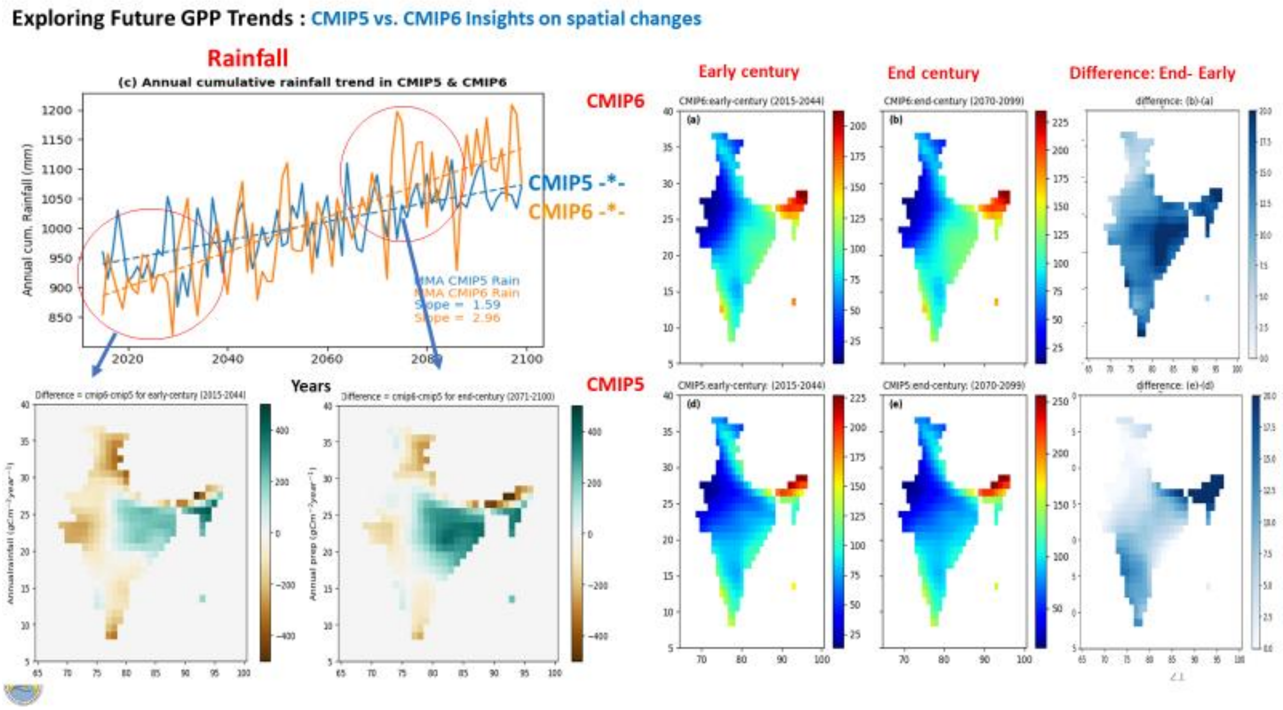
Slide 11: We checked if there was increase in previous generation of models also. For that, we compared commonly available CMIP models from the previous generation CMIP5 with CMIP6 models. We got 5 common models with similar experiments. CMIP6 models show approx. 30% higher trend than in comparison to CMIP5 models.

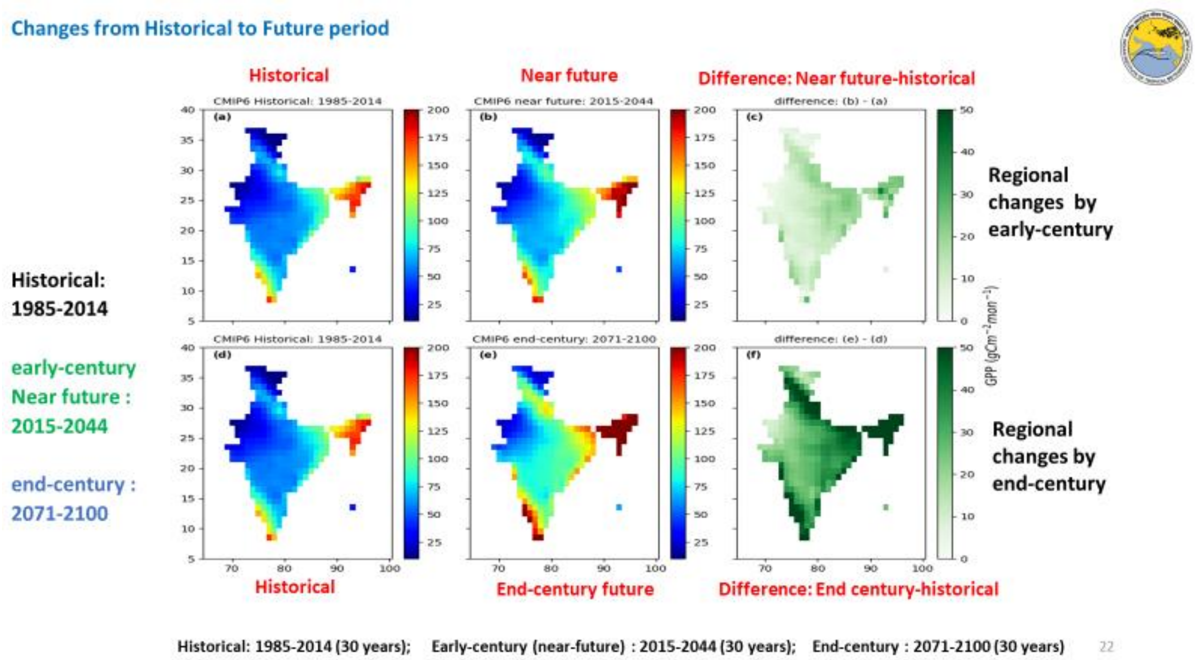
CMIP5 Vs CMIP6

CMIP5 esmrcp85, 2006-2100 r1i1p1 — CMIP6: esmssp585, 2015-2100, r1i1p1f1

S. No.	Institute	Model Name CMIP5	Corresponding CMIP6 model	Atmosphere resolution	Land Carbon and BGC	N_2 cycle CMIP5	Reference CMIP5
1	CCCma	CanESM2	CanESM5	2.81×2.81	CLASS2.7+CTEM1	No	Arora and Boer. 2010
2	MIROC	MIROC-ESM	MIROC5	2.81×2.81	MATSIRO+SEIB DGVM	No	Watanabe et al. 2011
3	MPI	MPI-ESM-LR	MPI-ESM1.2-LR	1.88×1.88	JSBACH	No	Reick et al. 2013
4	MRI	MRI-ESM1	MRI-ESM2.0	3.2×1.6	LPJ-DGVM at ecosystem level	No	Adachi et al. 2013
5	NorESM	NorESM1-ME	NorESM2-MM	1.88×2.50	CLM4	Yes	Tjiputra et al. 2013







Overall, this analysis suggests that the increased GPP in the models having a possible connection to increased precipitation in models.