International Journal of Advanced Biochemistry Research

ISSN Print: 2617-4693
ISSN Online: 2617-4707
NAAS Rating (2025): 5.29
IJABR 2025; 9(12): 255-263
www.biochemjournal.com
Received: 02-09-2025
Accepted: 05-10-2025

AP Tathe
PG Scholar, College of Agriculture Pune, MPKV, Rahuri, Maharashtra, India

VM Londhe
Assistant Professor, Department of Agronomy, ARS, Niphad, Nashik, Maharashtra, India

SV Bagade
Head, Department of Agril. Meteorology, College of Agriculture, Pune MPKV, Rahuri, Maharashtra, India

VA Sthool
Former Head, Department of Agril. Meteorology College of Agriculture, Pune MPKV, Rahuri, Maharashtra, India

AA Bhagat
Assistant Professor of Statistics Division of Economics, College of Agriculture, Pune MPKV, Rahuri, Maharashtra, India

Corresponding Author:
AP Tathe
PG Scholar, College of Agriculture Pune, MPKV, Rahuri, Maharashtra, India

Relation of EL-Nino and Indian Ocean Dipole (IOD) with rainfall and production of major *Kharif* crops of Western Maharashtra

AP Tathe, VM Londhe, SV Bagade, VA Sthool and AA Bhagat

DOI: https://www.doi.org/10.33545/26174693.2025.v9.i12Sd.6502

Abstract
The present study entitled "Relation of El Nino and Indian Ocean Dipole (IOD) with Rainfall and production of major kharif crops in Western Maharashtra" was undertaken to evaluate the influence of major climatic oscillations on regional rainfall variability and their subsequent effects on agriculture. The analysis of district-wise average annual rainfall during strong El Nino years compared to normal years revealed a consistent decline across all districts of Western Maharashtra. This study analyzes the impacts of El Nino, Positive IOD, and Negative IOD events on major *kharif* crops rice, soybean, groundnut, and cotton in Western Maharashtra. During El Nino years, all crops experienced significant declines in area, production, and productivity, with the most severe impacts observed in Nandurbar, Solapur, Dhule, Ahilyanagar, Pune and Sangli due to reduced monsoonal rainfall and prolonged dry spells. In contrast, Positive IOD years generally improved rainfall distribution, resulting in expanded rice, soybean, and cotton cultivation in several semi-arid districts, though groundnut area declined in some regions. Cotton production and productivity improved notably in districts like Nandurbar and Sangli. During Negative IOD years, rice, soybean, groundnut and cotton showed mixed responses. Some districts experienced increased sown area, but overall production and productivity declined across most crops, particularly in Ahilyanagar, Nandurbar, Nashik and Dhule due to erratic rainfall and moisture stress. The findings highlight strong crop sensitivity to climate anomalies and emphasize the need for region-specific climate-resilient strategies.

Keywords: Negative IOD, Positive IOD, El Nino, *kharif and* semi-arid etc.

Introduction

Agriculture remains a cornerstone of the Indian economy, providing livelihoods, food security, and employment, especially for rural populations. Its productivity is closely linked to climatic factors such as temperature, rainfall, humidity, and sunshine, with the performance of the South-West monsoon being particularly decisive (Krishna Kumar *et al*., 2004; Selvaraju, 2003) [22]. Rainfall during the *Kharif* season (June-October) is vital for crops like rice, maize, soybean, and cotton, yet monsoon variability is substantially influenced by global climatic phenomena such as the El Nino-Southern Oscillation (ENSO) and the Indian Ocean Dipole (IOD), which affect rainfall distribution across India, especially in the western agro-climatic zones (Ashok *et al*., 2001 [3]; Gadgil & Gadgil, 2006) [5]. ENSO impacts agriculture in complex ways, as crop sensitivity varies across phenological stages, and water stress during flowering and grain filling can sharply reduce yields; regions most affected by El Nino often face drought-induced declines in production, with implications for food security (Rojas *et al*., 2014) [19].

In India, El Nino years typically coincide with weak monsoons and rising temperatures, heightening drought risks and reducing outputs of key summer crops such as rice, sugarcane, cotton, and oilseeds, which may contribute to inflation and lower GDP, though the ENSO-monsoon link is weaker than in regions like Australia and significant impacts occur mainly during strong El Nino events (Patel *et al*., 2014) [16]. The western agro-climatic zones including Rajasthan, Gujarat, Maharashtra, and parts of Madhya Pradesh are particularly vulnerable due to their arid and semi-arid climates (Kumar *et al*., 2004). El Nino, characterized by anomalous warming in the Pacific, disrupts global circulation patterns and has historically weakened Indian monsoon winds and rainfall (Rao *et al*., 2011; Krishna Kumar *et al*., 2006) [8], although post-1980s shifts in ENSO behavior and the emergence of

Central Pacific ENSO events have weakened this inverse relationship (Krishna Kumar *et al*., 1999 [9]; Krishna Kumar *et al*., 2006) [8].

Conversely, La Niña generally enhances monsoon rainfall but has shown altered effects in recent decades due to weakened Walker circulation (Samanta *et al*., 2020) [21]. The IOD also plays a critical role in monsoon modulation, with positive phases enhancing and negative phases reducing Indian Summer Monsoon Rainfall. Despite modest early correlations (Saji *et al*., 1999) [20], historical data from 1958-1997 indicate that most intense IOD events corresponded with respective rainfall anomalies, suggesting that increasing IOD variability may influence or weaken ENSO-monsoon linkages. The present study aims to examine the impact of South-West monsoon rainfall on the production of major *Kharif* crops in Western Maharashtra during El Nino and IOD conditions.

Material and methods

Daily rainfall data for ten districts of Western Maharashtra Pune, Satara, Sangli, Solapur, Kolhapur, Nashik, Ahilyanagar, Dhule, Nandurbar, and Jalgaon covering the period from 1993 to 2023 were collected from the Statistics Department and the Department of Agriculture, Government of Maharashtra; the India Meteorology Department (IMD), Pune; the Indian Meteorology Department, Pune; and the Department of Agricultural Meteorology, College of Agriculture, Pune. Data on the area, production, and yield of rice, soybean, groundnut, and cotton for the years 2000-01 to 2023-24 were obtained from the Directorate of Economics and Statistics, Government of Maharashtra. For each crop, average production across the selected districts was computed to evaluate long-term performance and regional variability, and additional averages for area, production, and yield were calculated for years influenced by El Nino and Indian Ocean Dipole (IOD) events to assess climate-induced impacts on agricultural productivity. El Nino years were identified using the Oceanic Nino Index (ONI), based on sea surface temperature anomalies in the Nino 3.4 region (5°N-5°S, 120°W-170°W), following the criteria of Jan Null (2011), which define an El Nino event as five consecutive overlapping three-month seasons with SST anomalies ≥ + 0.5 °C. To assess event severity, El Nino years were further categorized as weak (+ 0.5 °C to + 0.9 °C), moderate (+ 1.0 °C to + 1.4 °C), or strong (≥ + 1.5 °C). Accordingly, each study year was classified into non-El Nino, weak, moderate, or strong El Nino categories, and rainfall data for each district were grouped under these classes to facilitate comparative analysis. This classification enabled a detailed examination of crop performance under different El Nino phases, thereby providing insights into the effects of ENSO- and IOD-related climatic variability on agricultural productivity in Western Maharashtra.

Table 1: Classification of El Nino years based on SST anomaly

Intensity	Years
Weak	2004, 2006, 2014
Moderate	1994, 2002, 2009,
Strong	1997, 2015, 2023
La Nino/Non El Nino	Remaining 21 years (years with normal rainfall)

During the period considered for the present study from 1993 to 2023, there were 3 moderate, 3 strong and 3 weak El Nino events out of 30 years.

Table 2: Classification of IOD years based on ISMR anomaly

Intensity	Years
Positive	1994, 1998, 2003, 2005, 2010, 2016, 2019, 2020, 2022
Negative	1997, 2000, 2002, 2009, 2012, 2014, 2015, 2018, 2023
Neutral year/Normal year	Remaining 12 years (years with normal rainfall)

During the period considered for the present study from 1993 to 2023, there were 9 Positive IOD, 9 Negative IOD and remaining normal year's event out of 30 years.

The variation in rainfall pattern was calculated by Descriptive Statistics i.e. Standard deviation, variance & range etc. The impact of South-West Monsoon on Production of Major *Kharif* crops of Western Maharashtra during EL-Nino & IOD condition was tested with the help of Regression Analysis.

Results and Discussion

Effect of El-Nino on Average area, Production and Productivity of major *Kharif* crops

El Nino conditions were found to negatively affect food grain production in the region. District-wise analysis showed that many areas were highly vulnerable, with notable declines in average production during El Nino years compared to normal years. Reduced Southwest Monsoon rainfall during these periods significantly impacted yields. In Western Maharashtra, an examination of rice cultivation from 2000 to 2023 revealed consistent decreases in area sown, production, and productivity in all districts. These negative percentage changes reflect the strong dependence of rice cultivation on adequate monsoonal rainfall and highlight the adverse effects.

1. Rice

The analysis of district-wise changes in rice cultivation during El Nino years (2000-2023) in Western Maharashtra showed a declined in area sown, production, and productivity across all districts (Table 2). The negative percentage change indicated the adverse impact of El Nino-induced rainfall deficits on rice cultivation, which was highly dependent on monsoonal precipitation.

Most districts Rice cultivation observed a decrease in area sown during El Nino years. Notably, experienced significant reductions. The overall production of rice saw substantial declined in most districts. Nandurbar (48.07%), Solapur (42.86%), Dhule (39.03%) and Ahilyanagar (30.56%) were recorded the sharpest reductions in rice production.

Productivity (kg/ha) also showed a downward trend with Solapur (26.52%), Pune (22.08%), Sangli (19.59%) and Nandurbar (19.23%) among the worst-hit districts. Major rice-growing districts like Pune and Kolhapur also reported substantial reductions in both area and production. These declines reflected the combined effects of reduced area sown and lower production due to moisture stress during El Nino years. However, districts like Jalgaon showed a slight increased in productivity (8.79%), this is might be due to more favorable local conditions or better soil and irrigation management.

The variations in impact across districts can be attributed to differences in topography, soil type, and irrigation infrastructure**.** Districts in the rain-shadow region (Ahilyanagar, Solapur, and Dhule) experienced severe declines, while relatively humid regions like Kolhapur and Satara showed lesser reductions**.** The declined in productivity across other districts is consistent with previous reports that El Nino negatively affects rice yields due to erratic rainfall and prolonged dry spells (Kulkarni *et al*., 2001) [11].

2. Soybean

The analysis of district-wise changes in soybean cultivation during El Nino years (2000-2023) in Western Maharashtra showed a decline in area sown, production, and productivity across all districts (Table 3). The negative percentage change indicated the adverse impact of El Nino-induced rainfall deficits on soybean cultivation, which was highly dependent on monsoonal precipitation.

A significant reduction in the area sown was observed in Dhule (18%)**,** Pune (13.61%), Nandurbar (12.23%), Ahilyanagar (12.22%) and highlighting the severe impact of drought-like conditions on rsoybean farming. Similar declines in production were recorded, with Dhule **(**31.30**%)** and Nandurbar (28.02%) experiencing the highest losses. These findings align with previous studies indicating that El Nino weakens monsoonal rainfall, reducing water availability for rice cultivation (Gadgil *et al*., 2004; Kumar *et al*., 2006) [13].

Soybean productivity also declined in most districts, with the highest reductions in Nandurbar (17.20), Nashik (16.84) and Sangli (16.76%)**,** emphasizing the impact of moisture stress on crop yields.

Overall, the data aligns with previous studies that suggest El Nino events lead to weakened monsoonal circulation, affecting crop yields across India (Kumar *et al*., 2006 [13]; Rao *et al*., 2019) [18]. The observed reductions in Western Maharashtra underscore the vulnerability of regions dependent on monsoonal rainfall, particularly for water-intensive crops like soybean.

The findings highlight the need for adaptive agricultural practices, such as improved irrigation techniques, early warning systems, and crop diversification, to mitigate the adverse effects of future El Nino events.

3. Groundnut

The effect of El Nino on groundnut cultivation in Western Maharashtra from 2000 to 2023 was assessed by comparing district-wise average area sown, production, and productivity during El Nino years against normal years. The analysis revealed varying degrees of decline across these parameters, highlighted the adverse impact of El Nino-induced climatic variations aregiven in table 4. The highest decline was observed in Ahilyanagar (24.22%), followed by Jalgaon (9.58%). However, certain districts, such as Solapur (22.20%), Pune (9.47%) were recorded an increased in the sown area. The increase in these districts may be attributed to adaptive cropping strategies by farmers in response to erratic rainfall patterns during El-Nino years. Similar findings have been reported by Annonumous (2023) and Bhat *et al*., (2022), who observed shifts in cropping patterns in response to climate variability.

Groundnut production showed a declined trend across most districts during El-Nino years, with the highest reductions were recorded in Sangli (16.87%) and Ahilyanagar (16.37%). A marginal increase was observed in Kolhapur (2.29%), which could be attributed to better soil moisture retention and irrigation facilities. The reduction in production is primarily due to reduced precipitation and increased temperature stress, leading to poor pod formation and lower yields. Research by *Reddy et al*., (2020) corroborates these findings, highlighted that El-Nino-induced drought conditions significantly impact groundnut productivity.

Productivity, expressed as kg/ha, declined in all districts during El-Nino years. The most severe reductions were noted in Dhule (20.93%), Pune (14.80%) and Nashik (14.51%). The least affected district in terms of productivity loss was Kolhapur (2.95%). The decline in productivity can be attributed to moisture stress during the critical growth stages, leading to stunted growth and reduced kernel development. Similar trends were reported by Sharma *et al*., (2017), who emphasized the negative impact of El-Nino on oilseed crops, particularly in arid and semi-arid regions.

El Nino negatively impacted groundnut cultivation, particularly in rainfed regions. Districts with better irrigation, such as Kolhapur and Pune, showed resilience. Strategies like improved irrigation, moisture conservation, and drought-resistant varieties (Mamun *et al*., 2024) [15] can help mitigate future impacts.

4. Cotton

The impact of El Nino on cotton cultivation in Western Maharashtra was assessed by analyzing district-wise changes in average area sown (ha), production (tons), and productivity (kg/ha) during El Nino years compared to normal years from 2000 to 2023. The results indicated a decline in most districts, highlighting the vulnerability of cotton to climatic fluctuations in table 5.

The highest reduction was observed in Nashik (21.30%) and Ahilyanagar (19.1%) suggesting a shift in cropping patterns due to unfavorable weather conditions. Similarly, Jalgaon (8.11%), Dhule (9.30%) and Nandurbar (0.68%) also showed reductions in sown area. However, in districts like Solapur (10.24%) and Kolhapur (1.79%), a slight increase in area sown was recorded, possibly due to localized agronomic adaptations.

Cotton production declined significantly across major districts due to reduced rainfall and water stress. Sangli recorded the highest drop (22.21%), followed by Nandurbar (20.41%) and Satara (18.75%). Jalgaon (14.17%) showed similar trends. Kulkarni *et al*., (2016) [11] linked El Nino to lower *Kharif* crop yields, while Ullah *et al*., (2017) [24] highlighted water-efficient strategies to improve cotton yield under drought conditions.

The productivity of cotton, which reflected the yield per hectare, declined in all districts during El Nino years. The maximum reduction of productivity was recorded in Satara (22.94%), followed by Pune (18.92%) and Sangli (18.50%). The adverse impact on productivity can be attributed to prolonged dry spells, poor boll development, and increased pest infestations under drought-like conditions. Jalgaon (7.19%), Dhule (17.32%), Pune (18.92%) and Nandurbar (16.38%) also reported significant reductions in productivity. The decline in productivity is closely linked to increased temperatures and erratic rainfall, which lead to poor germination and reduced boll formation, as reported by Alotaibi (2023) [2] and Ahmed *et al*., 2019 [1] given adaptation strategies related to *Kharif* agronomic crops.

Additionally, Khan *et al*., (2018) [7] noted that water stress during the reproductive stage of cotton results in a significant yield penalty, a found that aligns with the present study. Similar observations were made by Gore and Ray (2022) [6], who highlighted that cotton yields in Maharashtra was highly susceptible to climatic extremes, particularly drought stress.

Table 2: Percent Change in District wise average area sown (ha), Production (tons), Productivity (kg/ha) of Rice during El-nino year compared to normal year of Western Maharashtra (2000 to 2023)

Name of District	Area		Production			Productivity		
	El-Nino	Normal	El-Nino	Normal	PC*	El-Nino	Normal	PC*
Nashik	911.43	979.66	911.43	979.66	-6.96	1318.00	1451.66	-9.21
Dhule	47.43	73.44	39.86	65.38	-39.03	884.60	1073.20	-17.57
Nandurbar	157.29	283.50	149.14	287.19	-48.07	903.40	1118.42	-19.23
Jalgaon	2.00	2.88	2.00	2.88	-30.56	480.57	441.75	8.79
Ahilyanagar	107.57	175.06	101.00	162.50	-37.85	880.60	1037.40	-15.11
Pune	852.57	1023.06	852.57	1023.06	-16.66	1324.43	1699.75	-22.08
Solapur	1.00	1.81	1.00	1.75	-42.86	416.80	567.25	-26.52
Satara	815.29	849.13	815.29	849.13	-3.99	1716.71	1793.75	-4.29
Sangli	330.71	395.00	330.71	395.00	-16.28	1864.86	2319.13	-19.59
Kolhapur	2794.57	2998.38	2794.57	2998.38	-6.80	2605.71	2814.00	-7.40

Table 3: Percent Change in District wise average area sown (ha), Production (tons), Productivity (kg/ha) of Soybean during El-nino year compared to normal year of Western Maharashtra (2000 to 2023)

Name of District	Area		Production			Productivity		
	El-Nino	Normal	El-Nino	Normal	PC*	El-Nino	Normal	PC*
Nashik	507.14	527.54	634.90	820.48	-22.62	1240.57	1491.72	-16.84
Dhule	112.86	137.63	107.58	156.59	-31.30	1207.20	1394.50	-13.43
Nandurbar	187.29	213.38	231.64	321.81	-28.02	1191.80	1439.38	-17.20
Jalgaon	190.43	206.00	285.71	300.44	-4.90	1552.34	1612.10	-3.71
Ahilyanagar	620.29	552.75	518.20	615.81	-15.85	1001.71	1104.60	-9.31
Pune	106.86	123.69	198.74	266.75	-25.50	1956.86	1970.81	-0.71
Solapur	230.86	206.81	148.92	192.81	-22.76	1006.71	1172.94	-14.17
Satara	435.71	477.06	708.14	898.88	-21.22	1673.14	1863.06	-10.19
Sangli	534.00	534.38	820.00	987.44	-16.96	1539.47	1849.44	-16.76
Kolhapur	576.00	537.31	1045.57	1130.06	-7.48	1830.29	2046.90	-10.58

Table 4: Percent Change in District wise average area sown (ha), Production (tons), Productivity (kg/ha) of Groundnut during El-nino year compared to normal year of Western Maharashtra (2000 to 2023)

Name of District	Area		Production			Productivity		
	El-Nino	Normal	El-Nino	Normal	PC*	El-Nino	Normal	PC*
Nashik	266.86	291.56	220.14	250.38	-12.08	823.86	963.69	-14.51
Dhule	227.14	225.88	146.14	158.00	-7.51	578.14	731.19	-20.93
Nandurbar	57.00	53.63	34.57	40.38	-14.39	667.54	778.19	-14.22
Jalgaon	30.29	33.50	25.00	27.06	-7.61	852.29	884.50	-3.64
Ahilyanagar	52.71	69.56	38.94	46.56	-16.37	608.57	670.20	-9.20
Pune	344.14	314.38	306.14	331.31	-7.60	883.29	1036.75	-14.80
Solapur	35.29	28.88	16.71	16.94	-1.36	469.43	543.10	-13.56
Satara	474.00	446.63	561.43	598.94	-6.26	1189.86	1354.31	-12.14
Sangli	306.86	299.13	252.71	304.00	-16.87	870.00	995.00	-12.56
Kolhapur	555.14	521.88	812.00	793.81	2.29	1464.86	1509.31	-2.95

Table 5: Percent Change in District wise Average Area sown (ha), Production (tons), Productivity (kg/ha) of Cotton during El-nino year compared to normal year of Western Maharashtra (2000 to 2023)

Name of District	Area		Production			Productivity		
	El-Nino	Normal	El-Nino	Normal	PC*	El-Nino	Normal	PC*
Nashik	330.57	420.06	598.10	688.13	-13.08	233.50	270.30	-13.61
Dhule	1458.14	1593.75	1878.64	2243.40	-16.26	203.40	246.00	-17.32
Nandurbar	755.14	760.25	907.80	1140.60	-20.41	220.30	263.44	-16.38
Jalgaon	4437.57	4797.56	7379.57	8598.25	-14.17	278.43	300.00	-7.19
Ahilyanagar	752.00	930.19	1102.67	1228.40	-10.24	211.86	235.47	-10.03
Pune	1.25	1.29	3.00	2.81	6.76	231.57	285.60	-18.92
Solapur	13.57	12.31	22.14	21.25	4.19	258.29	307.44	-15.99
Satara	14.00	15.00	16.86	20.75	-18.75	195.80	254.10	-22.94
Sangli	15.71	14.94	16.29	20.94	-22.21	178.15	218.60	-18.50
Kolhapur	0.57	0.56	0.71	0.56	26.79	99.42	109.70	-9.37

Effect of Positive IOD on Average area, Production and Productivity of Major *Kharif* crops

The Indian Ocean Dipole (IOD), particularly its positive phase, significantly influences the monsoonal patterns in India, often enhancing rainfall over central and western parts of the country (Ashok *et al*., 2001) [3]. The present study analyzed the impact of Positive IOD years on the average area, production, and productivity of soybean in various districts of Western Maharashtra over the period from 2000 to 2023.

1. Rice

Positive Indian Ocean Dipole (IOD) years (2000-2023) generally enhanced rice cultivation in Maharashtra, with notable spatial variability. As shown in Table 6, most districts recorded increases in area, production, and productivity compared to normal years due to favorable climatic conditions.

Semi-arid districts such as Solapur (78.66%), Sangli (35.83%), and Ahilyanagar (31.8%) saw the largest expansion in cultivated area, indicating that improved rainfall encouraged additional land use. In contrast, established rice-growing districts like Kolhapur (1.91%) and Pune (2.31%) showed marginal increases due to already saturated rice areas (Gadgil *et al*., 2007).

Production also rose substantially, particularly in Solapur (130.33%) and Nandurbar (51.45%), with gains driven by both increased area and higher productivity. However, districts like Sangli and Ahilyanagar exhibited only modest production growth despite large area increases, likely due to agro-climatic or input constraints (Rathore *et al*., 2013).

Overall, enhanced rainfall during positive IOD years improves soil moisture, reduces crop stress, and extends the growing season, leading to better performance across parameters. These findings align with earlier studies linking positive IOD events to strengthened monsoon rainfall and improved rainfed crop yields (Gadgil & Gadgil, 2006) [5].

2. Soybean

The performance of soybean during Positive Indian Ocean Dipole (IOD) years showed considerable spatial variability across western Maharashtra (Table 7). Most districts recorded an increase in area sown, with the largest expansions in Solapur (139.99%), Pune (117.84%), and Dhule (47.43%), likely due to improved monsoon rainfall encouraging farmers to expand cultivation (Kumar *et al*., 2001) [14]. In contrast, Sangli (−16.79%) and Kolhapur (−3.82%) showed declines, possibly due to crop preference shifts, localized climatic effects, or waterlogging in high-rainfall zones (Rathore *et al*., 2013).

Soybean production also increased in most districts, especially in Pune (97.67%) and Nandurbar (30.08%), while decreases in Sangli (−22.55%) and Kolhapur (−5.5%) suggest that factors such as soil conditions, management practices, or extreme rainfall may have offset the benefits of favorable monsoon conditions (Bhatla *et al*., 2023) [4].

Productivity trends were mixed: increases occurred in Nandurbar (21.11%), Pune (1.89%), Nashik (2.1%), and marginally in Kolhapur (0.29%). However, major declines in Solapur (−31.46%), Ahilyanagar (−7.13%), and Dhule (−6.98%) indicate that excessive moisture, poor rainfall distribution, pest/disease pressures, or waterlogging may have negatively affected yields. The sharp productivity drop in Solapur despite a large expansion in area suggests cultivation of marginal lands or suboptimal practices. Similar declines in Satara, Sangli, and Jalgaon may be linked to delayed sowing, lodging, pest incidence, or nutrient leaching.

Overall, the findings align with earlier studies showing that IOD events significantly influence monsoon variability and crop outcomes in India (Kripalani & Kumar, 2004) [12]. While Positive IOD phases can enhance production potential, district-specific adaptation is essential for sustaining productivity.

3. Groundnut

The impact of Positive Indian Ocean Dipole (IOD) years on groundnut cultivation in Western Maharashtra (2000-2023) showed substantial spatial variability across districts (Table 8). Most districts recorded a decline in area sown during Positive IOD years, with the largest reductions in Nandurbar (26.56%), Pune (22.61%), and Dhule (15.96%). These decreases likely reflect shifts in cropping patterns driven by climatic uncertainty and rainfall variability during IOD events, consistent with findings by Gadgil *et al*. (2002). Only Jalgaon (10.32%) and Ahilyanagar (8.44%) showed increases, suggesting localized adaptability or irrigation support.

Production trends generally mirrored area changes. Districts such as Kolhapur (-12.37%), Satara (-10.06%), and Pune (-22.61%) experienced significant declines, likely due to reduced sown area and inconsistent rainfall. Jalgaon again showed a positive shift (10.32%), indicating localized resilience, in line with Selvaraju (2003) [22], who noted that local agro-climatic conditions can counter broader climate signals like the IOD.

Productivity exhibited mixed patterns. Declines in Kolhapur (-6.69%), Solapur (-13.96%), and Ahilyanagar (-11.89%) suggest moisture stress or poor rainfall distribution. However, districts such as Nashik (11.42%), Jalgaon (10.38%), and Sangli (10.34%) showed notable productivity gains, possibly due to effective resource management or favorable intra-seasonal rainfall during IOD events (Ashok *et al*., 2004). Interestingly, Nandurbar, despite major declines in area and production, showed a 7.54% rise in productivity, indicating efficient input optimization when cultivation is reduced.

4. Cotton

The percent changes in cotton area sown, production, and productivity during Positive Indian Ocean Dipole (IOD) years (2000-2023) across western Maharashtra (Table 9) show substantial spatial variability. Most districts recorded an expansion in cotton area during Positive IOD years, with Jalgaon (4907.86%) and Dhule (1756.00%) showing the largest increases. These expansions likely reflect improved rainfall distribution and soil moisture during Positive IOD phases, which enhance monsoon performance (Saji *et al*., 1999) [20]. In contrast, cotton-limited districts such as Kolhapur (-0.29%), Pune (-1.14%), and Solapur (-7.14%) saw declines, possibly due to cropping shifts or heightened sensitivity to climatic anomalies.

Production trends largely paralleled area changes. Nandurbar (47.33%), Pune (76.40%), and Dhule (32.30%) recorded notable production gains, again reflecting favorable monsoonal impacts that reduce water stress and support crop growth.

Productivity patterns, however, varied widely. Sangli showed a significant productivity increase (34.07%) despite declines in area and production, suggesting intensive management or supportive microclimates. Other districts with increased productivity included Satara (11.20%), Nashik (10.50%), and Nandurbar (8.65%). Conversely, Ahilyanagar (-14.56%), Jalgaon (-4.43%), and Kolhapur (-59.56%) experienced declines, likely due to excessive rainfall, pest pressures, or management challenges that offset climatic benefits. These findings support earlier work suggesting that although Positive IOD generally enhances cotton potential through improved monsoon conditions (Yamagata *et al*., 2004) [25], district-level responses depend heavily on local agronomic and environmental conditions.

Table 6: Percent Change in District wise Average Area Sown (ha), Production (tons), Productivity (kg/ha) of Rice during Positive IOD year compared to Normal year of Western Maharashtra (2000 to 2023)

Name of District	Area		Production			Productivity		
	Positive IOD	Normal	Positive IOD	Normal	PC*	Positive IOD	Normal	PC*
Nashik	688.14	592.78	1168.57	854.67	36.7	1623.57	1400.00	15.96
Dhule	64.63	59.67	83.14	63.22	31.48	1294.43	1012.11	27.89
Nandurbar	237.00	213.33	353.57	233.44	51.45	1484.00	1038.33	42.94
Jalgaon	1.86	1.78	2.43	1.78	36.52	582.78	582.78	0
Ahilyanagar	134.00	101.67	186.00	152.11	22.26	1315.44	1315.44	0
Pune	601.00	587.44	1066.71	1026.11	3.96	1789.14	1633.44	9.53
Solapur	5.86	3.28	4.86	2.11	130.33	572.57	549.44	4.21
Satara	470.71	403.33	836.14	872.89	-4.22	1849.56	1849.56	0
Sangli	163.14	120.11	368.00	375.67	-2.04	2265.00	2174.33	4.17
Kolhapur	1057.14	1037.33	2956.71	3051.00	-3.09	2840.56	2840.56	0

Table 7: Percent Change in District wise Average Area sown (ha), Production (tons), Productivity (kg/ha) of Soybean during Positive IOD year compared to normal year of Western Maharashtra (2000 to 2023)

Name of District	Area		Production			Productivity		
	Positive IOD	Normal	Positive IOD	Normal	PC*	Positive IOD	Normal	PC*
Nashik	596.00	442.33	943.43	732.33	28.83	1688.86	1654.11	2.1
Dhule	147.43	100.00	190.43	135.56	40.45	1309.86	1408.22	-6.98
Nandurbar	220.14	194.89	346.00	266.00	30.08	1538.00	1269.67	21.11
Jalgaon	226.00	194.22	319.43	314.44	1.59	1620.86	1675.00	-3.23
Ahilyanagar	617.14	540.11	863.00	767.78	12.37	1288.29	1387.00	-7.13
Pune	165.00	75.78	365.29	184.78	97.67	2276.00	2233.56	1.89
Solapur	278.43	116.00	250.00	149.22	67.56	1064.00	1552.33	-31.46
Satara	557.57	403.11	1020.29	770.78	32.36	1738.86	1848.78	-5.95
Sangli	512.86	616.44	865.86	1118.00	-22.55	1701.29	1803.67	-5.68
Kolhapur	542.57	564.11	1072.00	1134.33	-5.5	2042.00	2048.00	-0.29

Table 8: Percent Change in District wise average area sown (ha), Production (tons), Productivity (kg/ha) of Groundnut during Positive IOD year compared to normal year of Western Maharashtra (2000 to 2023)

Name of District	Area		Production			Productivity		
	Positive IOD	Normal	Positive IOD	Normal	PC*	Positive IOD	Normal	PC*
Nashik	275.00	312.22	276.71	286.56	-11.94	1047.71	940.33	11.42
Dhule	203.71	242.44	155.71	178.33	-15.96	767.86	760.44	0.98
Nandurbar	44.86	61.11	37.71	48.22	-26.56	840.00	781.11	7.54
Jalgaon	33.71	30.56	32.00	25.22	10.32	992.57	899.22	10.38
Ahilyanagar	73.14	67.44	53.71	56.89	8.44	728.29	826.56	-11.89
Pune	288.43	372.67	299.14	357.89	-22.61	1045.71	958.67	9.08
Solapur	27.57	28.67	16.43	17.78	-3.84	562.57	653.89	-13.96
Satara	423.00	470.33	541.57	635.33	-10.06	1310.71	1380.22	-5.03
Sangli	292.57	305.78	299.14	276.00	-4.33	995.86	902.56	10.34
Kolhapur	488.71	557.67	708.00	864.78	-12.37	1441.86	1545.22	-6.69

Table 9: Percent Change in District wise average area sown (ha), Production (tons), Productivity (kg/ha) of Cotton during Positive IOD year compared to normal year of Western Maharashtra (2000 to 2023)

Name of District	Area		Production			Productivity		
	Positive IOD	Normal	Positive IOD	Normal	PC*	Positive IOD	Normal	PC*
Nashik	412.43	380.56	945.00	724.44	30.45	317.00	286.78	10.5
Dhule	1756.00	1364.67	2887.29	2182.67	32.3	261.00	256.89	1.6
Nandurbar	831.57	656.33	1473.57	999.78	47.33	266.43	245.22	8.65
Jalgaon	4907.86	4645.78	9744.29	8627.44	12.93	297.86	311.67	-4.43
Ahilyanagar	1049.43	734.89	1731.57	1348.67	28.36	257.00	300.78	-14.56
Pune	1.14	0.78	3.14	1.78	76.4	344.14	338.44	1.68
Solapur	7.14	10.00	11.86	15.56	-23.77	324.71	311.67	4.19
Satara	10.14	15.22	12.00	25.33	-52.64	293.43	263.89	11.2
Sangli	10.29	17.22	15.43	27.33	-43.55	292.57	218.11	34.07
Kolhapur	0.29	0.56	0.29	0.78	-62.82	48.57	120.11	-59.56

Effect of Negative IOD on Average area, Production and Productivity of major *Kharif* crops

1. Rice

Table 10. show that rice cultivation in western Maharashtra during Negative IOD years (2000-2023) exhibited strong spatial variability in area, production, and productivity. Several districts-Kolhapur (159.27%), Satara (67.61%), Solapur (61.59%), Nashik (61.36%), and Sangli (100.72%) recorded substantial increases in rice area, likely due to the above-normal rainfall associated with Negative IOD events, which encouraged expansion into both traditional and marginal rice-growing zones (Ashok *et al*., 2001) [3]. In contrast, Ahilyanagar (-42.16%), Dhule (-38.31%) and Nandurbar (-29.59%) showed declines, possibly due to waterlogging, unsuitable soils, or a shift toward more resilient crops under adverse moisture conditions.

Despite area expansion in certain districts, rice production declined widely. Major reductions occurred in Ahilyanagar (-61.33%), Dhule (-41.81%), and Nandurbar (-32.63%), suggesting that excessive moisture, delayed sowing, and disease pressure reduced yields during Negative IOD phases (Saji *et al*., 1999) [20]. However, Jalgaon (113.48%) and Solapur (151.18%) showed large production increases from relatively small cultivation areas, possibly reflecting localized management efforts or intensified cultivation.

Productivity dropped across all districts, with the most severe declines in Ahilyanagar (-59.45%), Jalgaon (-44.59%), and Solapur (- 41.58%). Even traditionally strong rice-growing districts like Kolhapur (- 7.58%) and Satara (-11.13%) experienced reduced yields. These declines align with earlier findings that Negative IOD years often bring waterlogging, nutrient leaching, and heightened pest/disease incidence, all of which suppress rice productivity (Tripathi *et al*., 2007) [23].

5.2 Soybean

Table 11, show that soybean cultivation in western Maharashtra during Negative IOD years (2000-2023) experienced mixed responses across districts. Soybean area increased notably in Solapur (114.14%), Pune (59.80%), and Nashik (23.74%), likely due to enhanced rainfall enabling expansion in moisture-limited regions (Ashok *et al*., 2001) [3]. In contrast, Sangli (- 20.01%), Jalgaon (-4.85%), and Kolhapur (-4.69%) recorded declines, suggesting crop shifts toward varieties better suited to high-rainfall conditions.

Despite area increases in many districts, production generally declined. Major reductions occurred in Ahilyanagar (-59.45%), Nashik (- 23.11%), and Sangli (-23.80%), indicating that excess rainfall may have caused waterlogging, disease, or delayed maturity (Saji *et al*., 1999) [20]. Only a few districts, such as Pune (7.61%) and Satara (2.36%), saw slight production gains.

Productivity trends were predominantly negative. Sharp declines in Ahilyanagar (- 59.45%), Solapur (- 28.76%), Nashik (- 23.11%), and Sangli (- 23.80%) reflect the adverse impacts of excessive moisture during Negative IOD phases. However, Pune (7.61%) and Satara (2.36%) maintained or slightly improved productivity, likely due to better crop management or more favorable local conditions.

5.3 Groundnut

Table 12, indicate that groundnut cultivation in western Maharashtra experienced widespread negative impacts during Negative IOD years (2000-2023). Groundnut area declined in most districts, with the steepest reductions in Nandurbar (-21.30%), Ahilyanagar (-16.84%), and Nashik (-16.62%), likely due to erratic rainfall discouraging farmers from planting this moisture-sensitive crop (Ashok *et al*., 2001) [3]. A slight increase in area was observed only in Solapur (12.62%), possibly due to favorable rainfall timing that supported sowing.

Production also dropped sharply across nearly all districts. The most severe declines were in Nandurbar (-51.06%), Ahilyanagar (-42.15%), and Dhule (-41.47%), reflecting adverse impacts of excessive rainfall on crop development and pod filling (Saji *et al*., 1999) [20]. Even districts with relatively small area reductions, such as Kolhapur (-9.24%) and Sangli (-7.37%), experienced decreased output.

Productivity showed a consistent downward trend across all districts, with major declines in Dhule (-34.91%), Nandurbar (-31.32%), and Solapur (-30.72%). These reductions highlight the crop's vulnerability to excess moisture stress during critical growth stages, a common feature of Negative IOD years (Ummenhofer *et al*., 2009). Smaller productivity declines in Pune (-3.34%), Kolhapur (-3.71%), and Sangli (-3.79%) may be attributed to comparatively better soils, irrigation support, or effective crop management.

5.4 Cotton

Table 13, show that cotton cultivation in western Maharashtra experienced varied responses during Negative IOD years (2000-2023). Cotton area displayed mixed trends: significant increases occurred in Pune (28.62%), Solapur (85.00%), and Nandurbar (28.69%), likely reflecting crop shifts influenced by altered rainfall patterns or farmers' risk management strategies (Ashok *et al*., 2001) [3]. In contrast, Nashik (-3.17%), Satara (-4.07%), and Kolhapur (-28.57%) recorded declines, possibly due to unfavorable early-season weather.

Despite area expansion in several districts, production declined widely. Major reductions in Ahilyanagar (-38.74%), Nashik (-43.95%), and Jalgaon (-16.21%) suggest that climatic conditions during Negative IOD years were suboptimal for cotton growth. Only Sangli (3.91%) showed a marginal production increase.

Productivity was adversely affected in almost all districts. The steepest declines were observed in Ahilyanagar (-42.11%), Nashik (-32.48%), Dhule (-35.24%), and Kolhapur (-44.65%), reflecting stresses such as erratic rainfall, waterlogging, or elevated pest pressure—conditions commonly intensified during Negative IOD phases (Ullah *et al*., 2017) [24]. Sangli (7.57%) was the sole district to show a productivity increase, likely due to favorable microclimatic conditions or effective crop management.

Table 10: Percent Change in District wise average area sown (ha), Production (tons), Productivity (kg/ha) of Rice during Negative IOD year compared to normal year of Western Maharashtra (2000 to 2023).

Name of District	Area		Production			Productivity		
	Negative IOD	Normal	Negative IOD	Normal	PC*	Negative IOD	Normal	PC*
Nashik	956.7	592.78	956.7	854.67	11.93	1325.5	1400.00	-5.32
Dhule	36.8	59.67	36.8	63.22	-41.81	750.8	1012.11	-25.82
Nandurbar	157.3	223.33	157.3	233.44	-32.63	759.4	1038.33	-26.87
Jalgaon	3.8	2.78	3.8	1.78	113.48	322.9	582.78	-44.59
Ahilyanagar	58.8	101.67	58.8	152.11	-61.33	533.4	1315.44	-59.45
Pune	913.0	627.44	913.0	1026.11	-10.99	1413.5	1633.44	-13.47
Solapur	5.3	3.28	5.3	2.11	151.18	320.9	549.44	-41.58
Satara	793.5	473.33	793.5	872.89	-9.11	1643.8	1849.56	-11.13
Sangli	341.4	170.11	341.4	375.67	-9.13	1961.8	2174.33	-9.76
Kolhapur	2793.6	1077.33	2793.6	3051.00	-8.43	2625.4	2840.56	-7.58

Table 11: Maharashtra (2000 to 2023) Percent Change in District wise average area sown (ha), Production (tons), Productivity (kg/ha) of Soybean during Negative IOD year compared to normal year of Western Maharashtra (2000 to 2023).

Name of District	Area		Production			Productivity		
	Negative IOD	Normal	Negative IOD	Normal	PC*	Negative IOD	Normal	PC*
Nashik	547.3	442.33	563.1	732.33	-23.11	1123.7	1654.11	-23.11
Dhule	134.9	100.00	133.9	135.56	-1.22	1005.9	1408.22	-1.22
Nandurbar	212.8	194.89	248.8	266.00	-6.47	1228.8	1269.67	-6.47
Jalgaon	184.8	194.22	257.5	314.44	-18.1	1540.4	1675.00	-18.1
Ahilyanagar	592.9	540.11	311.3	767.78	-59.45	690.1	1387.00	-59.45
Pune	121.1	75.78	198.8	184.78	7.61	1650.5	2233.56	7.61
Solapur	249.4	116.00	106.3	149.22	-28.76	920.1	1552.33	-28.76
Satara	459.9	403.11	789.0	770.78	2.36	1844.0	1848.78	2.36
Sangli	493.3	616.44	851.9	1118.00	-23.8	1647.1	1803.67	-23.8
Kolhapur	537.6	564.11	1109.4	1134.33	-2.2	2071.8	2048.00	-2.2

Table 12: Percent Change in District wise average area sown (ha), Production (tons), Productivity (kg/ha) of Groundnut during Negative IOD year compared to normal year of Western Maharashtra (2000 to 2023)

Name of District	Area		Production			Productivity		
	Negative IOD	Normal	Negative IOD	Normal	PC*	Negative IOD	Normal	PC*
Nashik	260.3	312.22	212.9	286.56	-25.72	825.0	940.33	-12.26
Dhule	209.9	242.44	104.4	178.33	-41.47	495.0	760.44	-34.91
Nandurbar	48.1	61.11	23.6	48.22	-51.06	536.6	781.11	-31.32
Jalgaon	30.5	30.56	20.8	25.22	-17.5	787.5	899.22	-12.43
Ahilyanagar	56.1	67.44	32.9	56.89	-42.15	589.5	826.56	-28.68
Pune	320.1	372.67	307.6	357.89	-14.06	926.6	958.67	-3.34
Solapur	32.3	28.67	15.1	17.78	-15.15	453.0	653.89	-30.72
Satara	446.1	470.33	547.1	635.33	-13.91	1219.6	1380.22	-11.63
Sangli	292.3	305.78	255.6	276.00	-7.37	868.3	902.56	-3.79
Kolhapur	527.3	557.67	785.0	864.78	-9.24	1487.8	1545.22	-3.71

Table 13: Percent Change in District wise average area sown (ha), Production (tons), Productivity (kg/ha) of Cotton during Negative IOD year compared to normal year of Western Maharashtra (2000 to 2023)

Name of District	Area		Production			Productivity		
	Negative IOD	Normal	Negative IOD	Normal	PC*	Negative IOD	Normal	PC*
Nashik	368.5	380.56	406.1	724.44	-43.95	193.6	286.78	-32.48
Dhule	1637.0	1364.67	1657.5	2182.67	-24.05	166.4	256.89	-35.24
Nandurbar	844.5	656.33	917.3	999.78	-8.25	181.0	245.22	-26.17
Jalgaon	4704.3	4645.78	7230.6	8627.44	-16.21	255.0	311.67	-18.18
Ahilyanagar	827.1	734.89	826.0	1348.67	-38.74	174.1	300.78	-42.11
Pune	3.0	1.78	4.9	2.78	17.28	155.4	338.44	-54.08
Solapur	18.5	10.00	31.4	15.56	101.67	269.4	311.67	-13.55
Satara	14.6	15.22	21.4	25.33	-15.52	246.8	263.89	-6.47
Sangli	18.1	17.22	28.4	27.33	3.91	234.6	218.11	7.57
Kolhapur	0.4	0.56	0.4	0.78	-48.72	66.5	120.11	-44.65

Conclusion

El Nino years adversely affected the area, production, and productivity of rice, soybean, groundnut and cotton. Positive IOD years supported favorable rainfall and promoted expansion of rice and soybean in Solapur, Pune and Dhule, though waterlogging in some areas reduced productivity.

Negative IOD years led to uneven rainfall across districts, causing contrasting crop performance with some regions gaining while others experienced severe yield losses.

References

1. Ahmed I, Ullah A, Rahman MH, Ahmad B, Wajid SA, Ahmad A, Ahmed S. Climate Change Impacts and Adaptation Strategies for Agronomic Crops. IntechOpen; 2019. doi: 10.5772/intechopen.82697.
2. Alotaibi M. Climate change, its impact on crop production, challenges, and possible solutions. Notulae Botanicae Horti Agrobotanici Cluj-Napoca. 2023;51(1):13020.
3. Ashok K, Guan Z, Yamagata T. Impact of the Indian Ocean Dipole on the relationship between the Indian monsoon rainfall and ENSO. Geophysical Research Letters. 2001;28(23):4499-4502.
4. Bhatla R, Bhattacharyya S, Verma S, Mall R, Singh R. El Nino/La Nina and IOD impact on Kharif season crops over western agro-climatic zones of India. Theoretical and Applied Climatology. 2023;151(3):1-14.
5. Gadgil S, Gadgil S. The Indian monsoon, GDP and agriculture. Economic and Political Weekly. 2006;41(47):4887-4895.
6. Gore PG, Ray KC. Variability in drought incidence over districts of Maharashtra. Mausam. 2022;53(1):533-538.
7. Khan A, Pan X, Ullah N, Tan D, Sh F, Zahoor R, Luo H. Coping with drought: stress and adaptive mechanisms, and management through cultural and molecular alternatives in cotton as vital constituents for plant stress resilience and fitness. Biological Research. 2018;51:47.
8. Krishna Kumar K, Patwardhan SK, Kulkarni A, Kamala K, Koteswara Rao K, Jones R. Simulated projections for summer monsoon climate over India by a high-resolution regional climate model (PRECIS). Current Science. 2006;91(3):346-353.
9. Krishna Kumar K, Rajagopalan B, Cane MA. On the weakening relationship between the Indian monsoon and ENSO. Science. 1999;284(5423):2156-2159.
10. Krishna Kumar K, Rupa Kumar K, Ashrit RG, Deshpande NR, Hansen JW. Climate impacts on Indian agriculture. International Journal of Climatology. 2004;24(11):1375-1393.
11. Kulkarni A, Gadgil S, Patwardhan S. Monsoon Variability, the 2015 Marathwada Drought and Rainfed Agriculture. Current Science. 2016;111(7):1182-1193.
12. Kumar KK, Rajagopalan B, Cane MA. On the weakening relationship between the Indian monsoon and ENSO. Science. 2004;284(5423):2156-2159.
13. Kumar KK, Rajagopalan B, Hoerling M, Bates G, Cane M. Unraveling the mystery of Indian monsoon failure during El Niño. Science. 2006;314(5796):115-119.
14. Kumar R, Gautam RH. Climate change and its impact on agricultural productivity in India. Journal of Climatology and Weather Forecasting. 2014;2(1).
15. Mamun MAA, Li J, Cui A, Chowdhury R, Hossain ML. Climate-adaptive strategies for enhancing agricultural resilience in southeastern coastal Bangladesh: Insights from farmers and stakeholders. PloS One. 2024;19(6):e0305609.
16. Patel HR, Lunagaria MM, Pandey V, Sharma PK, Rao BB, Rao VUM. El Nino episodes and agricultural productivity in Gujarat. Techn. Report No. 01/2014-15. Department of Agricultural Meteorology, AAU; 2014.
17. Rao VUM, Subba AVM, Bapuji RB, Ramana RBV, Sravani RC, Venkateswarlu B. El Niño effect on climatic variability and crop production: A case study for Andhra Pradesh. Research Bulletin No. 2/2011. Central Research Institute for Dryland Agriculture; 2011.
18. Rao VUM, Subba AVM, Bapuji RB, Ramana RBV, Sravani RC, Venkateswarlu B. El Nino effect on climatic variability and crop production: A case study for Andhra Pradesh. Research Bulletin. 2019;2.
19. Rojas N, Li Y, Cumani R. Understanding the drought impact of El Nino on the global agricultural areas: An assessment using FAO’s agricultural stress index (ASI). Environment and Natural Resources Management Series. Food and Agriculture Organization of the United Nations; 2014.
20. Saji NH, Goswami BN, Vinayachandran PN, Yamagata T. A dipole mode in the tropical Indian Ocean. Nature. 1999;401(6751):360-363.
21. Samanta D, Rajagopalan B, Karnauskas KB, Zhang L, Goodkin NF. La Niña’s diminishing fingerprint on the central Indian summer monsoon. Geophysical Research Letters. 2020;47(2):e2019GL086237.
22. Selvaraju R. Impact of El Niño-Southern Oscillation on Indian food grain production. International Journal of Climatology. 2003;23(2):187-206.
23. Tripathi P, Chaturvedi A, Singh AK. Agro-climatic analysis of rice productivity in rainfed areas of Eastern Uttar Pradesh during southwest monsoon period. Asian Journal of Environmental Science. 2007;2(1):28-35.
24. Ullah A, Sun H, Yang X, Zhang X. Drought coping strategies in cotton: increased crop per drop. Plant Biotechnology Journal. 2017;15(3):271-284.
25. Yamagata T, Behera SK, Luo JJ, Masson S, Jury MR, Rao SA. Coupled ocean-atmosphere variability in the tropical Indian Ocean. In: Wang C, Xie SP, Carton JA, editors. Earth Climate: The Ocean-Atmosphere Interaction. American Geophysical Union; 2004:189-212.