University of Rome “Sapienza”
Department of Mathematics

II Level Master Course in Scientific Calculus

Studies of Numerical Climate Geoengineering: a focus on the Indian Monsoon Region

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To mum and dad, who always push me forward

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Abstract

This thesis work is a numerical study of the geoengineering technique recently proposed as a methodology to control climate change, particularly global warming.
In the actual situation of difficult political and economic international connections among countries, the global warming finds not a very fertile soil, despite its widespread acknowledged danger if we do not immediately revert the actual trend. This would require a pressing and revolutionary transformation in both global energy production and consumption system, together with the deployment of mitigation (implementing measures for cutting the emissions) and adaptation (safeguard from catastrophes) programs. In this complex context, it is crucial to assess the feasibility of various proposal to 'gain more time' by directly influencing the world climate and cooling the Earth sooner and/or faster: this might involve the so-called geoengineering, defined as the deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming. Among the various geoengineering methods recently proposed, because of its good effectiveness vs. affordability, we have chosen to focus attention on the injection (at one point on the Equator or uniformly globally) of proper amounts of SO_2 or sulphate aerosols so as to keep the global average temperature nearly constant. This method is part of the Solar Radiation Management (SRM) approach, which aims to reflect back to space a (small) fraction of the incident solar radiation. These techniques are already demonstrating to be highly controversial: there are, in fact, large uncertainties about their impacts on regional scales. Moreover, they do not address neither the main cause of climate change (i.e., the greenhouse gases concentrations augment), nor its impacts such as ocean acidification that are not directly related to temperature rise. Not to mention the fact that, once deployed, these methods require a long-term commitment by the global society. For these reasons, before seriously taking into account the deployment of whatsoever geoengineering method, the aftermaths on all scales should be carefully analysed. The number of studies of this type is by now very poor.
A numerical study concerning the consequences following the deployment of the geoengineering G3 scenario is here performed, with a specific focus on possible alterations of the Indian summer monsoon.
The work is organised as follows: in Ch.(1) we present the geoengineering methods and the major trends in literature; in Ch.(2) we sketch the main features of the models and data archives we have used; then, we give the first results of our numerical analysis for near-surface air temperature and precipitation on global scale in Ch.(3); finally, we show our outcomes for the Indian precipitation regimes in Ch.(4) and the Indian summer monsoon, focusing on the December-January-February and June-July-August seasons. Eventually, in Ch.(5) we sum up the conclusions and give final remarks.

Contents

1 Geoengineering the Climate **7**
1.1 The climate IS changing: the COP21 agreement 7
1.2 The energy balance of the Earth 9
1.3 The Search for a B-plan 11
1.3.1 Mitigation and Adaptation 12
1.3.2 Geoengineering 14
1.3.3 CDR vs SRM methods 15
1.3.4 Feasibility and Costs 19
1.3.5 The Moral Hazard Problem 21
1.4 Stratospheric Sulphate Aerosol Injection 22

2 The Numerical Models **25**
2.1 Models, Data and Method 25
2.1.1 HadGEM2-ES, RCP 4.5 27
2.2 The G3 Experiment 29
2.2.1 BADC Archive and CDO Tool 30

3 Numerical Simulations and Results **33**
3.1 Global Scale 33
3.1.1 Annual 33
3.1.2 Seasonal 37

4 The Focus on India **49**
4.1 The Indian Summer Monsoon in a Nutshell 49
4.2 Results and Comments from the Analysis of the Data 51

5 Conclusions and Final Remarks **63**

Bibliography **65**

Chapter 1

Geoengineering the Climate

1.1 The climate IS changing: the COP21 agreement

Despite of the nonsenses stated by the (less and less) skeptics and negationists about the undeniable climate changes, they are happening, and their impacts and costs will be large, serious, and unevenly spread.

The need to face them, has finally brought almost 200 countries to seat together and find an agreement. On December 12, 2015 the delegations of the 196 participating countries have eventually flattened most of their discords and approved an important new agreement on climate. The 31 pages text approved at the Paris Conference on climate and released by the UNFCCC (the United Nation Framework Convention on Climate Change) starts from the fundamental premise that: “The climate change represents a urgent and potentially irreversible threat for human societies as well as for the entire planet”. It thus requires for “the highest cooperation and effort of all the countries” with the intent of “accelerating the decrease of greenhouse gases[1] emissions”.

However, as for the previous ineffective Copenhagen agreement (following the Kyoto one), to be valid and enter into force it must be ratified, accepted or officially approved by at least 55 countries representing 55% of the world greenhouse gases (GHGs) emission on the whole. If on one side this time there has been global consensus (included the biggest polluters, USA, China, India that committed to cut their emissions for the first time), on the other side the Paris agreement, like the previous

[1]They are atmospheric gases of natural (e.g. water) and anthropogenic origin (Chlorofluorocarbors, CFCs) that absorb and emit radiation at specific wavelengths within the spectrum of thermal infrared radiation emitted by the Earth’s surface, the atmosphere itself and by clouds. This property causes the greenhouse effect.

Kyoto one, is a non-binding international protocol: it relies on voluntary allegiance of each of the 196 member countries of the UNFCCC (for the Kyoto protocol, this fact has wasted 8 years in vain). Once ratified, the protocol will rest on the principle of common but differentiated responsibility: the developing countries (particularly China and India, that are also the first and third world most polluting countries) will have less stringent limits achievable in much more time. The 21st Conference of Parties, or COP 21, has also set the long-term target of keeping the global warming far below the 2 °C threshold with respect to the pre-industrial age, demanding for efforts to strike the goal of 1.5 °C. These efforts are meant to be subject to revision every 5 years starting from 2023, in order to possibly progressively improve the target.

Also, it establishes the introduction of 100 billion dollars climate fundings for the 2020-2025 period, with the aim of implementing measures both for cutting the emissions (mitigation) and for safeguard from catastrophes, especially caused by floods and droughts, in the poor countries (adaptation). However, this plan is not in the binding part of the agreement.
Another critical point concerns the extraction of fossil fuels, which will proceede without any limit for many years. In fact, the Paris protocol does not set any limit for the exploitation of carbon, gas and oil. The only request is the achievement of the emission peak as soon as possible so as to reach an "equilibrium between anthropogenic emissions [...] and the absorption of the greenhouse gases reservoirs in the second half of this century". It has thus passed the principle of the climatic neutrality rather than that of zero emissions and de-carbonisation of the economies (scaring the industry). Even for deforestation no binding target has been set for its sensible reduction.

To be optimistic, this agreement is a first step for facing the irreversible damages caused by climate change. In fact, to effectively try to face the effects of climate change, the treaty should have been globally binding, with a maximum tolerable raise of the mean global temperature of 1.5 °C within the end of this century, a target of 100% renewable energy sources and a phase out of the fossil fuels within 2050. As a chain effect, this would have been triggered the transfer of about 100 billion non repayable dollars per year (starting from 2020) for mitigation and adaptation programs, especially for the countries geographically most vulnerable to climate change (and often also the poorest economies).

One of the criticism of the environmental associations as well as of most of the scientific world concerns the first revision of the national targets, set for the period 2018-2023, as if the world continues polluting at the current rates for three more years, it would be impossible to fulfil the targets of the Paris agreement. To worsen the situation, the checks will be self-certified by each country instead of an international commission.

1.2 The energy balance of the Earth

The temperature of our planet is determined by the balance at the top of the atmosphere between the mainly short-wave (ultraviolet and visible light) solar radiation absorbed and the long-wave thermal infrared radiation re-emitted to space. Any imbalance in these energy fluxes constitutes a 'radiative forcing'[2] that ultimately causes an adjustment of the global mean temperature until balance is restored, thus controlling the Earth's temperature and consequently driving and maintaining the climate system.

These radiation streams do not reach or leave the Earth's surface unimpeded, as one third of the incoming solar radiation on average is reflected by clouds, ice caps and bright surfaces. This reflectivity of the Earth (and more generally of other celestial surfaces) is referred to as its 'albedo'. Most of the incoming radiation passes through the atmosphere and reaches the Earth's surface, where some is reflected and most is absorbed, thus warming the surface. Then, some of the outgoing thermal radiation emitted by the Earth's surface is absorbed by the GHGs in the atmosphere and by clouds, reducing the amount of heat radiation escaping to space and warming the atmosphere and the soil more. On average, only 60% of the thermal radiation emitted by the surface of our planet eventually leaves the atmosphere after repeated absorption and re-emission within the atmosphere.

The outgoing thermal radiation increases strongly as the surface temperature increases while the incoming solar radiation does not. This creates a strong negative feedback, because the temperature of the surface and the atmosphere increase until the outgoing and incoming radiation reach a new state of equilibrium, and then stabilises. Taking into account that the flux of solar energy on the Earth's surface, that is the 'solar constant', averaged over the globe is approximately 342 W/m^2, and that more than 30% of it is reflected back to space, these leaves 235 W/m^2 entering the atmosphere and be absorbed by our climate system. In equilibrium, an equal flux of infrared radiation leaves the Earth (see Fig.1.1). This is a very delicate balance: if either radiation stream is perturbed by 1% (i.e. 2.35 W/m^2), the surface temperature will change[IPCC, 2007] by about 1.8 °C.

Increase in atmospheric greenhouse gas concentrations (e.g. CO_2, CH_4, N_2O, ground level ozone, O_3, and CFCs) due to human activities such as fossil fuel burning, deforestation and conversion of land for agriculture, have upset this delicate balance as the gases restrict the emission of heat radiation to space more than usual. To

[2]Radiative forcing is the change in the net, downward minus upward, irradiance (in units of W/m^2) at the tropopause due to a change in an external driver of climate change such as, for instance, a change in the concentration of carbon dioxide or the output of the Sun.

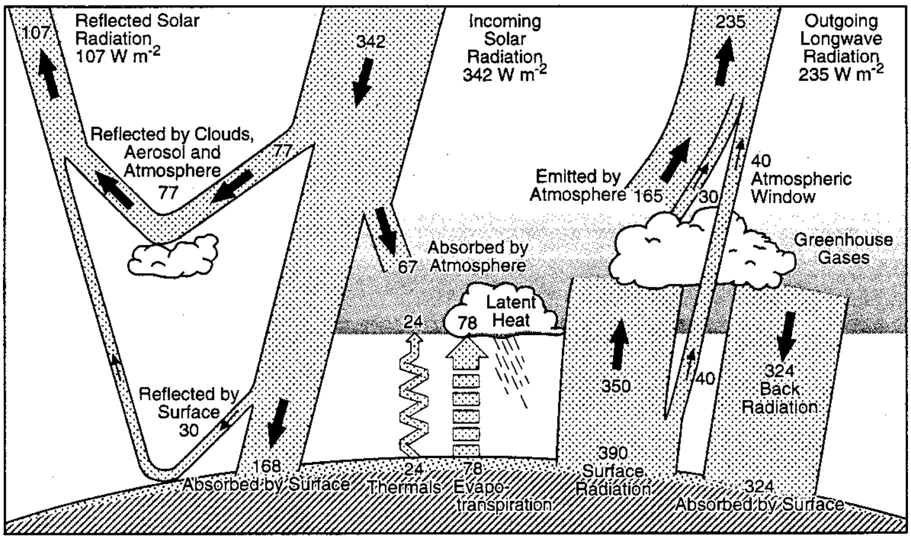


Figure 1.1: Schematic showing of the global average energy budget of the Earths atmosphere. Yellow indicates solar radiation; red indicates heat radiation and green indicates transfer of heat by evaporation/condensation of water vapour and other surface processes. The width of the arrow marks the magnitude of the flux of radiation and the numbers show annual average values. At the top of the atmosphere the net absorbed solar radiation is balanced by the heat emitted to space [Kiehl & Trenberth, 1997].

restore this imbalance, the lower atmosphere has warmed and is emitting more heat (long-wave) radiation. Of course and unfortunately, this warming will continue as the system evolves to approach a new equilibrium. In this framework, the role played by the carbon cycle is fundamental: in fact, it deeply influences the rate at which equilibrium can be restored by mediating the concentrations of greenhouse gas in the atmosphere.

Carbon is exchanged naturally between the land, oceans and atmosphere. Large quantities are stored in natural 'sinks'[3] on land and in the oceans, the deep ocean and vegetation and soils being the largest reservoirs. Every year, about 60 to 90 gigatons (Gt) of carbon are absorbed from the atmosphere by the vegetation of both the land surface and the surface ocean and an equivalent amount is released to the atmosphere. Prior to the industrial revolution, the fluxes of carbon exchange (that is, the carbon cycle) balanced closely. As shown in Fig. 1.2, today there is a flux of approximately 2 Gt/y from the atmosphere into each land and ocean[4], which only partially offsets the

[3]With sink it is meant any process or activity which removes a pollutant or precursor gas from the atmosphere or ocean.

[4]The absorption of the increase in atmospheric CO_2 by the ocean has led to a continuous decline in the average pH of the oceanic surface waters. This worrying phenomenon is known as the 'ocean acidification' and will continue in the future with increasing CO_2 levels [IPCC, 2007].

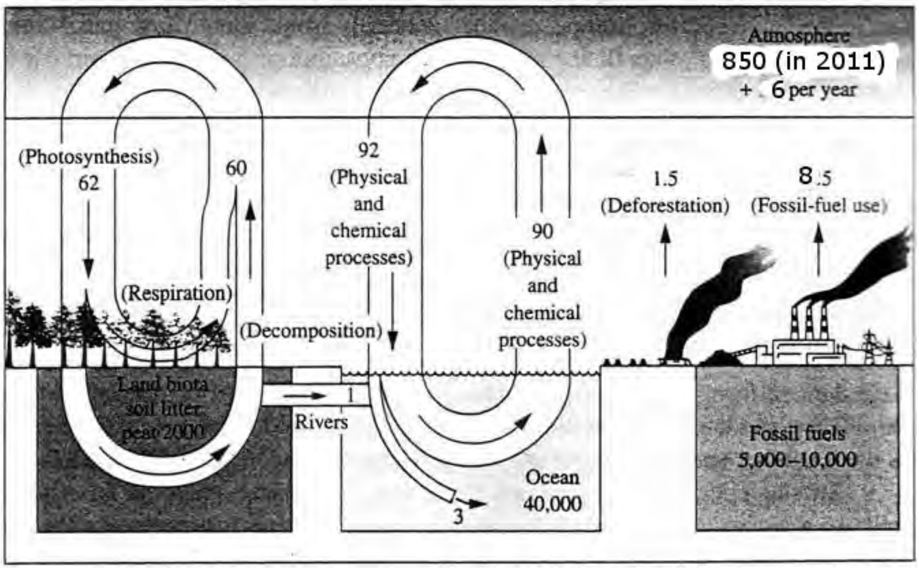


Figure 1.2: Global fluxes and reservoirs of carbon in Gt/y and Gt, respectively [De Nevers, 2000]

land-use change and fossil fuel fluxes releasing CO_2 in the atmosphere. This directly reflects on the mean global temperature: human activities since pre-industrial times are estimated to have produced a net radiative forcing of about 1.6 W/m^2, about half of which has been balanced by a global warming of 0.8 °C to date (this lag in the response of the global mean temperature is primarily due to the large heat capacity of the oceans, which only warm up slowly). A doubling of the CO_2 concentration from its pre-industrial value to 550 part-per-million (ppm) would give a radiative forcing of about W/m^2 and an estimated equilibrium average global warming of about 3 °C (in a range that goes from 2 to 4.5 °C)[IPCC, 2007].

1.3 The Search for a B-plan

If on a side the treaty of Paris will allow for the first time the coordination of the greenhouse gases emission policies of the participating countries, on the other it turns out to be definitely below the expectations. The executive UNFCCC secretary, Christina Figueres, stated that indeed "the contributions (as agreed by the 196 countries at the COP21) have the skill of limiting the foreseen raise of the mean global temperature to about 2.7 °C by 2100. That is absolutely not sufficient, but by the way far below the four or five degrees foreseen by some scientists". According to another estimate published by the United Nations Environment Programme (UNEP), the tasks of the countries will translate into a raise of the mean global temperature of 3-3.5 °C within 2100, unless global greenhouse gases emissions are cut by at least 50% of 1990 levels by 2050.

To further clarify the question we are here dealing with, we are faced with climate models that are unanimous in indicating a urgent need to limit atmospheric CO_2 to a concentration that would prevent most damaging climate change focusing on a goal of 500±50 parts per million (ppm), or less than double the preindustrial concentration of 280 ppm, to avoid global warming exceeding the 2 °C threshold [Allen et al., 2009]. The current concentration is about 400 ppm (being 375 ppm in 2009 [Keeling & Whorf, 2000]). The CO_2 emissions reductions necessary to achieve any such target depend on the emissions judged likely to occur in the absence of a focus on carbon (called a business-as-usual, BAU, trajectory), the quantitative details of the stabilisation target, and the future behaviour of natural sinks for atmospheric CO_2 (i.e., the oceans and terrestrial biosphere).

Very roughly, stabilisation at 500 ppm requires that emissions be held near the present level of 7 billion tons of carbon (GtC) per year for the next 50 years, even though they are currently on course to more than double.

And the problem could be indeed worsened by the additional effects due to non-CO_2 greenhouse gases and tropospheric aerosols whose contributions at present and in the recent past have roughly cancelled, but may definitely not do so in the future.

1.3.1 Mitigation and Adaptation

What mentioned above would require a revolutionary transformation of global energy production and consumption systems: to develop the revolutionary technologies required for such large emissions reductions in the second half of the century, enhanced research and development would have to begin immediately.

Humanity already possesses the fundamental scientific, technical, and industrial know-how to solve the carbon and climate problem for the next half-century. A portfolio of technologies now exists to meet the worlds energy needs over the next 50 years limiting atmospheric CO_2 to a trajectory that avoids a doubling of the preindustrial concentration. Every element in this portfolio has passed beyond the laboratory bench and demonstration project (many are even already implemented somewhere at full industrial scale).

With this in mind, the climate scientific community usually refers to the issues of 'mitigation' and 'adaptation' to climate change. These terms are fundamental in the climate change debate: roughly speaking, our present age has proactive options (mitigation), and must also plan to live with the consequences (adaptation) of global warming.

Mitigation

More specifically, climate mitigation is any action taken to permanently eliminate or reduce the long-term risk and hazards of climate change to human life, properly.

The International Panel on Climate Change (IPCC) defines mitigation as an "anthropogenic intervention to reduce the sources or enhance the sinks of greenhouse gases." [IPCC, 2007] . Examples of actions that can be considered as being part of this context are energy efficiency, decarbonisation of the supply of electricity and fuels (by means of fuel shifting, carbon capture and storage, nuclear energy, and renewable energy), and biological storage in forests and agricultural soils (a detailed description of many of these options can be found in [Pacala & Socolow, 2004]).

In the United Nations Framework Convention on Climate Change (UNFCCC) three conditions are made explicit when working towards the goal of greenhouse gas stabilisation in the atmosphere, that is mitigation:

- That it should take place within a time-frame sufficient to allow ecosystems to adapt naturally to climate change;
- That food production is not threatened and;
- That economic development should proceed in a sustainable manner.

Adaptation

While mitigation tackles the causes of climate change, adaptation tackles the effects of the phenomenon.

In general the more mitigation there is, the less they will be the impacts to which we will have to adjust, and the less the risks for which we will have to try and prepare. Conversely, the greater the degree of preparatory adaptation, the less may be the impacts associated with any given degree of climate change.

The IPCC defined adaptation as the "adjustment in natural or human systems to a new or changing environment, in response to actual or expected climatic stimuli or their effects, which moderate harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation."

[IPCC, 2007]. So, essentially, this term means an understanding of how individuals, groups and natural systems can prepare for and respond to changes in climate or their environment.

A successful adaptation can reduce vulnerability by building on and strengthening existing coping strategies.

The UNFCCC refers to adaptation in several of its articles. For example, the art. 4.1(f) states that all Parties shall "Take climate change considerations into account, to the extent feasible, in their relevant social, economic and environmental policies and actions, and employ appropriate methods, for example impact assessments, formulated and determined nationally, with a view to minimising adverse effects on the economy, on public health and on the quality of the environment, of projects or measures undertaken by them to mitigate or adapt to climate change.".

There are of course limits to adaptation. Consider the example of small island developing states threatened by sea level rise. They have fewer options to adapt: sea defences are particularly costly and they can do very little to protect the tourism and fisheries that sustain the local economy. Thus, the idea that less mitigation means greater climatic change, and consequently requiring more adaptation is the basis for the urgent need to reduce the greenhouse gases emissions.

It is important to stress that climate mitigation and adaptation should not be seen as alternatives to each other, as they are not discrete activities but rather a combined set of actions in an overall strategy to reduce greenhouse gas emissions.

1.3.2 Geoengineering

Whilst it is still physically possible to deliver emissions reductions of the magnitude required by mid-century (see e.g[Royal Society, 2009], and references therein), there is little if no evidence that this transformation is occurring: atmospheric concentrations are already more than 400 ppm CO_2. What is worse is that they are still rising steadily, and it seems increasingly likely that they will exceed 500 ppm by mid-century approaching 1000 ppm by 2100 [Keeling & Whorf, 2000]. In addition, there is continuing uncertainty about crucial parameters such as climate sensitivity [IPCC, 2007; Allen et al., 2009], and the fact that some climate impacts, of which the causes are quite unknown and the aftermaths very uncertain, may be happening sooner than predicted (e.g. the low Arctic summer sea-ice minima). This situation is absolutely unbearable by our Planet.

The size of the transformation, the lack of effective societal response and the inertia to changing our energy infrastructure motivate the exploration of other strategies to be ready should they become necessary to cool the Earth sooner and/or faster. Such action[5] might involve the so-called geoengineering, defined as the deliberate large-scale intervention in the Earth's climate system, in order to moderate global warming.

The basic idea is not new: it dates back to the 1830s, with J. P. Epsy's suggestion of lighting huge fires so as to stimulate convective updrafts and change rain intensity and frequency of occurrence [Fleming, 1990]. Geoengineering has been considered for many reasons since then, ranging from making polar latitudes habitable to changing precipitation patterns.

It is important to stress that nothing now known about geoengineering options gives any reason to diminish the unescapable efforts parties agreeing to the UNFCCC should make, in particular to lower global emissions of at least 50% on 1990 levels by 2050, and more thereafter.

1.3.3 CDR vs SRM methods

Geoengineering methods are usually divided into two main classes both having the ultimate aim of reducing global temperatures but differing in their modes of action, timescales over which they are effective, temperature and most of all modification of precipitation patterns effects and other consequences. They are:

1. **Carbon Dioxide Removal** (CDR) techniques, which address the main root cause of climate change by removing CO_2 from the atmosphere[6]. They include:

    - Land use management, to protect or enhance land carbon sinks;
    - Biomass use for both carbon sequestration[7] and a carbon neutral energy source;
    - Enhancement of natural weathering processes[8] to remove CO_2 from the atmosphere;

[5] Always bearing in mind that the safest and most predictable method of moderating climate change is to take early and effective actions to reduce emissions of greenhouse gases.

[6] While it would be theoretically also be possible for geoengineering methods to remove greenhouse gases other than CO_2 from the atmosphere (like methane, CH_4 and nitrous oxide, N_2O), most of the methods proposed so far concern CO_2 because it is long-lived and present at relatively high concentrations.

[7] With this term it is meant the carbon storage in terrestrial or marine reservoirs.

[8] Weathering processes are any of the chemical or mechanical processes by which rocks exposed

- Direct engineered capture of CO_2 from ambient air;
- Enhancement of ocean uptake of CO_2, e.g. by fertilisation of the oceans with naturally scarce nutrients, or by increasing upwelling processes.

2. **Solar Radiation Management** (SRM) techniques, which directly modify the Earth's radiation balance between incoming radiation from the Sun (mainly short-wave ultraviolet and visible light) that acts to heat the Earth, and outgoing (long-wave) thermal infrared radiation which acts to cool it, by reflecting a small percentage of the Sun's light and heat back into space. Methods include:

   - Increasing the Eart's albedo, for example by brightening human structures, planting crops with high reflectivity, covering deserts with reflective material;
   - Enhancement of marine cloud reflectivity;
   - Mimicking the effects of volcanic eruptions by injecting sulphate aerosols into the lower stratosphere;
   - Placing shields or deflectors in space to reduce the amount of solar energy reaching the Earth.

The objective of both SRM and CDR methods is to intervene in the Earths climate system.

CDR methods operate on the atmospheric stock of CO_2, and require the drawdown of a significant fraction of this before affecting the energy balance. Whilst CDR methods therefore immediately augment efforts to reduce emissions, there is inevitably a delay of several decades before they would actually have a discernable effect on climate, even if it were possible to implement them immediately. The global-scale effect of CO_2 removal would be essentially the same as that of emissions reduction, except that if deployed on a large enough scale, it would also potentially allow global total net emissions to be made negative, therefore enabling (at least in principle) a return to lower concentrations on timescales of centuries rather than millennia.

By contrast, SRM methods operate directly on the radiative fluxes involved in the Earths energy balance, and so take effect relatively rapidly (although not immediately as the large thermal capacity of the ocean will slow the temperature response). SRM methods are the only way in which global temperatures could be reduced at short notice, should this become necessary. Careful attention should therefore be paid to the timescales (lead-times, response times and potential durations) of CDR and SRM methods, so that their implementation could (if needed) be effectively phased,

to the weather undergo changes in character and break down.

under different scenarios of climate change, and alongside other abatement strategies.

As for the technical feasibility and risks of different methods, geoengineering by CDR methods is technically feasible but slow-acting and relatively expensive. The direct costs and local risks of particular methods would differ considerably from each other but could be comparable to (or greater than) those of conventional mitigation.

The technologies for removing CO_2 and many of their consequences are very different from those of technologies for modifying albedo.

Implementation of SRM methods is also likely to be technically feasible at a direct financial cost of implementation that is small compared to the costs of the impacts of foreseeable climate change, or of the emissions reductions otherwise needed to avoid them. However, such comparisons should be undertaken with caution until better information is available on the costs involved in SRM development and implementation. The additional indirect costs associated with the effects of SRM cannot reliably be estimated at present but would need to be considered, and could be significant.

SRM methods, if widely deployed, could achieve rapid reductions in global temperatures (over a few years to a decade) at a rate and to a level that could not be achieved by mitigation, even if carbon emissions were reduced to zero instantly. However, all SRM methods suffer from the termination problem, and modelling studies indicate that the resulting climate would not be the same as the climate that would be achieved if CO_2 concentrations were reduced. For example, with a uniform reduction of solar radiation, tropical precipitation would probably be reduced. Studies show that it is not generally possible to accurately cancel more than one aspect of climate change at the same time, but there are serious deficiencies in the ability of current models to estimate features such as precipitation and storms, with corresponding uncertainties in the effects of SRM on such features. Nevertheless, it is very likely that a high-CO_2 climate, together with some reduction in solar forcing (achieved by engineering a small increase of albedo), would be much closer to a pre-industrial climate than to an unmodified high-CO2 climate [IPCC, 2013]. SRM methods may serve as a useful backup in the future if their risks prove to be manageable and acceptable, and mitigation action proves to be inadequate, or if it is believed that a tipping point of the climate system is approaching.

SRM methods, if widely deployed, could achieve rapid reductions in global temperatures (over a few years to a decade) at a rate and to a level that could not be achieved by mitigation, even if carbon emissions were reduced to zero instantly. SRM techniques are however not an ideal way to deal with climate change as they do not address all the effects and risks of climate change (ocean acidification, for example), there would probably be undesirable side effects (e.g., on stratospheric ozone), and they would introduce new, potentially large risks of possible unanticipated effects on the system. The large-scale adoption of SRM methods would create an artificial, approximate, and potentially delicate balance between continuing greenhouse warming and reduced solar radiation, which would have to be maintained, potentially for many centuries. It is doubtful that such a balance is really sustainable for such long periods of time, particularly if it results in continued and even increased emissions of CO_2 and other greenhouse gases (e.g., through the exploitation of unconventional fossil fuels). Research to improve understanding of risks and impacts and to reduce the uncertainties to an acceptable level would be necessary before any of the SRM techniques could be deployed, and research on SRM methods is therefore prudent and desirable.

It is important to note that relative to the impacts of climate change itself, the unintended impacts of geoengineering on the environment are likely to be less significant. However, the environmental impacts of most methods have not yet been adequately evaluated, but are likely to vary considerably in their nature and magnitude, and in some cases may be difficult to estimate. For all of the methods considered, but, particularly for SRM methods, the climate achieved is unlikely to be quite the same as that with the effects of climate change cancelled out exactly, particularly for critical variables other than temperature which are very sensitive to regional differences (such as e.g., weather systems, wind-speed and ocean currents). Precipitation is very sensitive to detailed aspects of climate, and is thus especially likely to be so affected, and is also notoriously difficult to predict. In the case of SRM methods these would include the ecological impacts of a high CO_2 world, and the unpredictable effects of the changes in natural systems caused by a forced response to decreased temperatures under high CO_2 conditions. In the case of CDR methods these would be the environmental impacts of the process itself, rather than its effects on climate, but for methods involving ecosystem manipulation these may nevertheless be substantial.

In Fig.1.3 the effectiveness of the methods is plotted against their affordability (the inverse of the cost for a defined magnitude of effect). This diagram is tentative and approximate and should be treated as no more than a preliminary and somewhat illustrative attempt at visualising the results of the sort of multi-criterion evaluation that is needed. However, even this preliminary visual presentation may already be useful, simply because an ideal method would appear as a large green symbol in the top right-hand quadrant of the figure, and no such symbol exists. The nearest approximation is for stratospheric aerosols, which is coloured amber, because of uncertainties over its side-effects. By the way, all SRM methods should be treated with caution as they create an artificial and only approximate balance between greenhouse

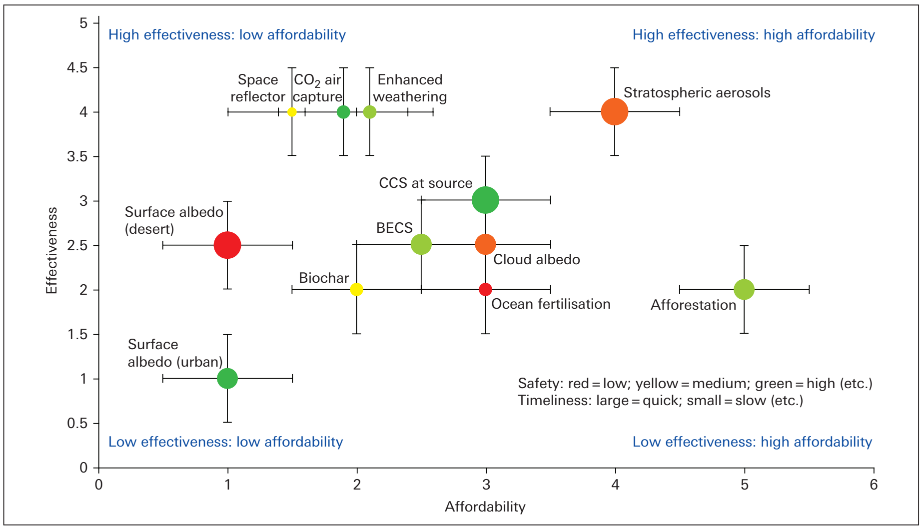


Figure 1.3: Effectiveness of the methods vs. their affordability [Royal Society, 2009]. The size of the points indicates their timeliness (on a scale of large if they are rapidly implementable and effective, through to small if not); their colours indicate their safety (on a scale from green if safe, through to red if not). Indicative error bars have been added to avoid any suggestion that the size of the symbols reflects their precision (even if not in scale, just to avoid confusing the diagram).

warming and reduced solar radiation which must be maintained actively, potentially for many centuries. Given that they do not reduce greenhouse gas concentrations, SRM methods are widely regarded only as options of last resort, and they should not be deployed without a clear and credible exit strategy, involving strong mitigation policies and (perhaps) the use of CDR methods which are sustainable. It would be risky to embark on major implementation of SRM methods without a clear and credible exit strategy, for example a phased transition after a few decades to more sustainable CDR methods. This implies that research would be needed in parallel on both SRM and CDR methods.

1.3.4 Feasibility and Costs

Despite of seeming sci-fi, and taking into account that all of the proposals considered are still in the early outline/concept stage and estimates of costs and environmental impacts are very tentative (an initial evaluation is possible using criteria based on the work of [Lenton & Vaughan, 2009], indeed the technology needed for some of the geoengineering proposals is already at disposal and ready.

Clearly, when developing climate change strategies and considering a potential role for geonegineering, decision makers should also take into account the appropriate balance of the relative contributions of mitigation, adaptation, and both CDR and

SRM methods, and the extent to which the risks of climate change may or may not outweigh the risks associated with geoengineering options, eventually weighing the appropriate timing and duration of all potential responses and interventions.

Thus, bearing in mind that none of the geoengineering methods offers a solution to climate change, neither they diminish the need for continued emissions reduction, there is the urgent need by decision makers to consider studies of feasibility for the various proposals. In this context, there is a range of criteria by which geoengineering proposals should be evaluated; these can be broadly grouped into technical criteria and social criteria. These are composites of several related criteria, and (except for costs) are defined so that a positive evaluation implies desirable features. They are:

1. Legality of the method proposed (regional/national/international).

2. Effectiveness (proven/unproven): including confidence in the scientific and technological basis, technological feasibility, and the magnitude, spatial scale and uniformity of the effect achievable.

3. Timeliness (of implementation and climate effect): including the state of readiness for implementation (and the extent to which any necessary experiments and/or modelling has been completed), and the speed with which the intended effect (on climate change) would occur.

4. Environmental, social and economic impacts (possibly including unintended consequences): including the predictability and verifiability of the intended effects, the absence of predictable or unintended adverse side-effects and environmental impacts (especially effects on inherently unpredictable biological systems), and low potential for things to go wrong on a large scale.

5. Costs (direct financial and carbon life cycle): of both deployment and operation, for a given desired effect (i.e. for CDR methods, cost per Gt of C, and for SRM methods, cost per W/m^2) evaluated over century timescales (or expressed as its inverse, i.e. affordability)[9].

6. Fundings (support for research and development and security over term for deployment).

7. Public acceptability (novelty/containability/scale of intervention/control frameworks): public attitudes, social acceptability, political feasibility and legality, which may change over time.

8. Reversibility (technological, political, social and economic): the ability to cease

[9]In practice, the information available on costs is extremely tentative and incomplete, and only order-of-magnitude estimates are possible.

a method and have its effects (including any undesired negative impacts) terminate within a short time, should it be necessary to do so.

On the basis of these criteria the likely costs, environmental impacts and possible unintended consequences are identified and evaluated so far as possible, so as to inform research and policy priorities.

1.3.5 The Moral Hazard Problem

All the concerns regarding the slow progress on achieving emissions reductions, added to uncertainties about climate sensitivity and climate parameters re-adjustment, have led some members of the scientific and political communities to suggest that geoengineering may offer an alternative solution to climate change mitigation. In response, concerns have been expressed that geoengineering proposals could reduce the fragile political and public support for mitigation and divert resources from adaptation. This question is addressed to as the 'moral hazard argument'. Moreover, geeingneering poses undoubtable significant potential environmental risks, and have large uncertainties in terms of effectiveness and feasibility: the wide range of proposals present a variety of social, ethical and legal issues that are only now beginning to be identified.

As geoengineering is a relatively new policy area, there are no regulatory frameworks in place aimed specifically at controlling these type of activities and, consequently, there exists the risk that some methods could be deployed by indigodual nations, corporations or even wealthy individuals without appropriate regulation or international agreement. While it is likely that some existing national, regional and international mechanisms may apply to either the activities themselves, or the impacts of geoengineering, they have yet to be analysed or tested with this purpose in mind. Recently, this has become an issue as organisations have shown interest in the potential of interventions such as ocean fertilisation to capture carbon. Commercial involvement in ocean fertilisation experiments has provoked a rapid and vocal response from the international political and scientific communities and environmental non-governmental organisations (NGOs).

Given the current poor state of understanding about geoengineering science, potentially useful techniques could be prematurely dismissed out of hand, and dangerous proposals may be promoted with enthusiasm. Policymakers need well-informed and authoritative advice based on sound science. With growing concern that geoengineering proposals were being promoted by some as a possible solution to the problem of climate change, that experiments were being undertaken, in some cases potentially in contravention of national or international laws, and that active investment in the development and testing of new technologies is occurring, some organisations, like the Royal Society, decided to undertake independent scientific reviews of the subject.

1.4 Stratospheric Sulphate Aerosol Injection

In this thesis work, we have decided to focus on the SRM method consisting in delivering sulphur species to the stratosphere (stratospheric sulphate aerosols). The decision follows the conclusions, well-known in literature and roughly summed up in Fig.1.3, that sulphate aerosols can counteract the globally averaged temperature increase associated with increasing greenhouse gases and reduce changes to some other components of the Earth system in a very rapid, technically feasibly and with affordable costs, although the potential side-effects (e.g., on stratospheric ozone and high-altitude tropospheric clouds) would need to be determined and found to be acceptably small (for a recent and quite comprehensive review of this method see [Rasch et al., 2008], and references therein).

This approach to cooling the planet goes back to the mid-70s, when Budyko (1974) suggested that, if global warming ever became a serious threat, we could counter it with airplane flights in the stratosphere, burning sulphur to make aerosols that would reflect sunlight away. The aerosols would increase the planetary albedo and cool the planet, ameliorating some of the effects of increasing CO_2 concentrations. The aerosols are chosen/designed to reside in the stratosphere because it is remote, and they will have a much longer residence time than tropospheric aerosols that are rapidly scavenged. The longer lifetime means that a few aerosols need to be delivered per unit time to achieve a given aerosol burden, and that the aerosols will disperse and act to force the climate system over a larger area.

Sulphate aerosols are always found in the stratosphere. Low background concentrations arise due to transport from the troposphere of natural and anthropogenic sulphur-bearing compounds. Occasionally, much higher concentrations arise from volcanic eruptions, resulting in a temporary cooling of the Earth system [Robock, 2000], which disappears as the aerosol is flushed from the atmosphere. The volcanic injection of sulphate aerosol thus serves as a natural analogue to the geoengineering aerosol. The analogy is not perfect because the volcanic aerosol is flushed within a few years, and the climate system does not respond in the same way as it would if the particles were continually replenished, as they would be in a geoengineering effort. Perturbations to the system that might become evident with constant forcing disappear as the forcing disappears [Rasch et al., 2008].

Thus, stratospheric aerosols are currently the most promising of the SRM methods because their effects would be more uniformly distributed than for localised Solar

Radiation Management methods, they could be much more readily implemented than space-based methods, and would take effect rapidly (within a year or two of deployment). However, potentially significant uncertainties and risks are associated with this approach and research into methods of delivery and deployment, effectiveness, impacts on stratospheric ozone and high-altitude tropospheric clouds, and detailed modelling of their impacts on all aspects of climate (including precipitation patterns and monsoons) is needed. Particularly, there are likely to be remaining regional climate changes (b.t.w. after geoengineering in general), with some regions experiencing significant changes in temperature or precipitation. This is a main topic to address and analyse as it would affect the lives of billions. To this aim, using a quite detailed (coupled) Atmosphere-Ocean General Circulation Model (AOGCM), Robock et al. (2008) found that injections of SO_2 to enhance stratospheric aerosol would modify the Asian and African summer monsoons, reducing precipitation and thus (like climate change) potentially impacting the food supply to billions of people. This type of studies have suggested that major regional effects could result from sulphate geoengineering, which could counteract or reinforce those associated with climate change itself. These issues are currently being explored via computational simulations although current AOGCM codes may not be adequate for such relatively fine-scale effects. This thesis inserts in this particular mainstream of research (see next Ch.3).

However, the approach may be useful in offering extra protection to particularly vulnerable regions like the Arctic.

Another side-effect to be addressed is the impact on the ozone layer: in fact, the aerosols also serve as surfaces for heterogeneous chemistry resulting in increased ozone depletion. Eventually, concerns have been expressed that deployment of stratospheric sulphates could lead to increased 'acid rain' and exacerbate ocean acidification. The quantities of sulphates added to the stratosphere would however be extremely small compared to both those of natural volcanic releases and the acidifying effect of CO_2 emissions and would therefore not directly cause any significant increase in the ocean acidification process. To this it should be added a range of feedback processes that may become important with a continually renewed stratospheric sulphate layer (as opposed to the transient effects from a volcanic eruption) [Royal Society, 2009].

Chapter 2

The Numerical Models

As stated in the previous chapter, geoengineering may provide useful tools for reducing global temperatures quite rapidly should the need arise. However, it is very important to stress that it would be the global mean temperature to be addressed. Otherwise stated, the global net alleviation of the climate, in the sense of taking the global warming under control, could deeply effect many climatic parameters including temperature and precipitation at both the global and regional scales (something like the cure could be worse than the disease, at least on a regional scale). This is what the (few) simulations tell us, indeed. That is why we insist underlining that the possibility of seriously taking into account the deployment of some geoengineering methods must previously unavoidably pass through a huge number of numerical simulations which may address the question of what would happen locally, i.e. on a regional scale.

For geographical zones like the overcrowded India, such studies become vital: a 1.2 billion people completely depending on the monsoon phenomenon could be faced to address tremendous floods and/or droughts, without enough time for adapting to the new climate.

It is in the view of these considerations that we have conducted this thesis work analysing the effects of the deployment of a specific geoengineering model (based on the equatorial deployment of a suitable quantity of sulphates) firstly on a global scale, then on the local scale of India.

In this chapter, we are going to describe the models, data archives some software used in the course of our study.

2.1 Models, Data and Method

The scientific understanding of the Earths climate system, including the central question of how the climate system is likely to respond to human-induced perturbations, is comprehensively captured in Global Climate Models (GCMs) and Earth System

Models (ESMs). Diagnosing the simulated climate response, and comparing responses across different models, is crucially dependent on transparent assumptions of how the GCM/ESM has been driven, especially because the implementation can involve subjective decisions and may differ between modelling groups performing the same experiment. Thus, useful climate projections depend on having the most comprehensive and accurate models of the climate system[1].

Atmosphere-ocean general circulation models (AOGCMs) have been widely used in the IPCC assessments to make projections of future climate change given greenhouse gas emission scenarios. AOGCMs are based on fundamental physical laws (Newtons laws of motion, conservation of energy, etc.). Then, a computer model of the atmosphere is used to calculate the state of the climate system (temperature, precipitation, winds, water vapour, etc.) for the whole atmosphere and ocean as a function of time. Typically the atmosphere and ocean are represented by a large number of cells whose spatial resolution will depend on computing power available. Typical horizontal atmospheric resolutions[2] are 2° x 2°. Thus, it is important to stress that atmospheric processes with typical scales less than this must be represented ('parameterised') empirically, introducing in such a way a degree of approximation and uncertainty.

Moist primitive equations are the mathematical transcription of the following fundamental physical conservation laws:

1. Zonal and meridional momentum balance equations;
2. Vertical momentum balance equation;
3. Heat balance equation;
4. Conservation of mass;
5. Conservation of water species: vapour, liquid and ice phases.

The physics of the model includes all those processes participating to atmospheric dynamics which are not explicitly resolved by the primitive equations. They can be separated into two categories:

i. Physical processes that do not pertain fluid dynamics, i.e. radiative heat transfer;

[1] Despite this fact, any single model will still have limitations in its application for certain scientific questions and it is increasingly apparent that we need a range of models to address the variety of applications.

[2] We remember that 1° in longitude or latitude is roughly equal to 111.3 km.

ii. Physical processes that do pertain fluid dynamics but that cannot be resolved by primitive equations (e.g., clouds, convection, boundary layer turbulence, surface fluxes, and in general processes that can be filtered by the hydrostatic approximation[3], or they can feature spatial or temporal scales that are smaller than those resolved by the model).

The physics of the model determines the sources and sinks of heat, momentum and moisture, fundamental drivers of the atmospheric circulation. Such processes, essential for a realistic climate simulation, are therefore parametrised in function of the resolved state of the atmosphere via best estimate approximate formulas derived by semi-empirical theories and expert judgment. In such a way, the model can be viewed as composed by two parts:the dynamical core, controlling the time evolution of the atmosphere (thanks to resolved fluid dynamical processes) via the integration of the primitive equations, and a set of parametrised physical processes that provide a forcing on the resolved state of the atmosphere. Then, the model equations are numerically time-forward integrated by a discretisation of the atmosphere in both the vertical direction and the horizontal plane. For the climate models used, the atmosphere is divided into layers corresponding to selected values of the vertical coordinates and different numerical techniques allow to solve the set of ordinary differential equations obtained from a series of approximations of the partial differential equations given by the primateve equations.

In the IPCC AR4 it is concluded that there is "considerable confidence" that AOGCMs "provide credible quantitative estimates of future climate change, particularly at continental and large scales". Confidence in these estimates is greater for some climate variables like temperature than for others like precipitation. This confidence is based on a large international effort to compare and evaluate climate models, including detailed study of recent climate change. The models capture well the observed global temperature record when anthropogenic and natural forcings are included. They also reproduce some important climate variability over the past century, as well as the impact of perturbations (for example, the eruption of Mt Pinatubo of 1991). There is less confidence in the ability of the current generation of AOGCMs to address regional scale changes, and bridging the spatial gap from global/continental to regional scales is a major research challenge.

2.1.1 HadGEM2-ES, RCP 4.5

All the data used for our analyses are part of the CMIP5 project, model HadGEM2-ES, experiment RCP 4.5 and G3.

[3] An approximation in geophysical fluid dynamics that is based on the assumption that the horizontal scale is large compared to the vertical scale, such that the vertical pressure gradient may be given as the product of density times the gravitational acceleration.

Phase 5 of the Coupled Model Intercomparison Project (CMIP5) is a standard experimental protocol for studying the output of coupled ocean-atmosphere GCMs. It provides a community-based infrastructure in support of climate model diagnosis, validation, intercomparison, documentation and data access. The purpose of these experiments is to address outstanding scientific questions that arose as part of the IPCC Fourth Assessment report (AR4) process [IPCC b, 2007], improve understanding of climate, and to provide estimates of future climate change useful to those considering its possible consequences and the effects of mitigation and adaptation strategies. CMIP5 began in 2009 and is meant to provide a framework for coordinated climate change experiments over a five year period and includes simulations for assessment in the IPCC Fifth Assessment Report (AR5) as well as others that extend beyond the AR5 (`http://cmip-pcmdi.llnl.gov/cmip5/`). More specifically, CMIP5 promotes a standard set of model simulations in order to evaluate how realistic the models are in simulating the recent past, provide projections of future climate change on two time scales, near term (out to about 2035) and long term (out to 2100 and beyond), and understand some of the factors responsible for differences in model projections, including quantifying some key feedbacks such as those involving clouds and the carbon cycle.

There are a number of new types of experiments proposed for CMIP5 in comparison with previous incarnations. The main focus and effort rests on the longer timescale ('centennial') experiments, including now emission-driven runs of models that include a coupled carbon-cycle. These centennial experiments are being performed at the Met Office Hadley Centre with the HadGEM2-ES Earth System model, ESMs, [Martin et al., 2011], a configuration of the Met Offices Unified Model (`http://www.metoffice.gov.uk/research/modelling-systems/unified-model/`). Briefly speaking, HadGEM2-ES ESM is a coupled AOGCM with atmospheric resolution of 1.875° x 1.25° with 38 vertical levels and an ocean resolution of 1° (increasing to 1/3° at the equator) and 40 vertical levels [Jones et al., 2011]. HadGEM2-ES also represents interactive land and ocean carbon cycles and dynamic vegetation with an option to prescribe either atmospheric CO_2 concentrations or to prescribe anthropogenic CO_2 emissions and simulate CO_2 concentrations. An interactive tropospheric chemistry scheme is also included, which simulates the evolution of atmospheric composition and interactions with atmospheric aerosols. The model timestep is 30 minutes (atmosphere and land) and 1 h (ocean). Extensive diagnostic output has being made available to the CMIP5 multi-model archive. Moreover, they include important climate forcing, among which we find: GHGs (CO_2, $N2_O$, CH_4, CFCs), ozone, black carbon, organic carbon, sulphate aerosols, land use, solar irradiance, volcanic aerosols implementation.

The CMIP5 simulations include 4 future scenarios, referred to as 'Representative Concentration Pathways' or RCPs [Moss et al., 2010]. These future scenarios have been generated by four integrated assessment models (IAMs) and selected from over 300 published scenarios of future greenhouse gas emissions resulting from socio-economic and energy-system modelling. Among these RCPs, we have chosen the more realistic one dubbed RCP 4.5 [Clarke et al., 2007], that is a stabilisation scenario in which total radiative forcing is stabilised shortly after 2100, without overshooting the long-run radiative forcing target level. More precisely, in the RCP 4.5 scenario, as outlined by Moss et al. (2008), the total radiative forcing in 2100 reaches and subsequently stabilises at 4.5 W m^{-2} (relative to pre-industrial levels). This stabilised forcing reflects a CO_2 equivalent concentration of 650 ppm. We have selected this scenario because it is somehow a 'central scenario[4]. The experimental protocol involves performing a historical simulation (defined for HadGEM2-ES as 1860 to 2005) using the historical record of climate forcing factors such as greenhouse gases, aerosols and natural forcings such as solar and volcanic changes. The model state at 2005 is then used as the initial condition for the 4 future RCP simulations. Further extension of the RCP simulations to 2300 is also implemented as detailed in the RCP White Paper (document 8 at `http://cmip-pcmdi.llnl.gov/cmip5/modelingdocuments.html`).

2.2 The G3 Experiment

Most of the studies mentioned in the previous chapter calibrated their estimates of the climate response to geoengineering aerosol based upon historical observations of the aerosol produced by volcanic eruptions. The analogy between a volcanic eruption and geoengineering via a sulphate aerosol strategy is imperfect. The aerosol forcing from an eruption lasts a few years at most, and eruptions occur only occasionally. There are many timescales within the Earth system, and their transient response to the eruption is not likely to be the same as the response to the continuous forcing required to counter the warming associated with greenhouse gases. Furthermore, we have no precise information on the role the eruptions might have on a world warmer than today. It is thus of interest to explore the consequences of geoengineering using a climate model, a tool (albeit imperfect) that can simulate some of the complexities of the Earth system, and ask how the Earths climate might change if one could successfully introduce particles into the stratosphere. To this aim, in 2011 a suite of standardised climate modelling experiments has been proposed to be performed by any interested modeling group. At

[4]Using a more optimistic scenario in which rapid mitigation is implemented would result in less robust results and is thus not likely to be as illuminating. Conversely, choosing a scenario with higher radiative forcing would reflect an irrational and unsustainable path, since if society cannot effectively mitigate greenhouse gas emissions, geoengineering would be needed on a massive scale for a long period of time, due to the long atmospheric lifetime of CO_2.

the same time, a coordinating framework for performing such experiments, known as the Geoengineering Model Intercomparison Project (GeoMIP), has also been established (`http://climate.envsci.rutgers.edu/GeoMIP/index.html`). The standard experiment suite consists of four experiments, all relevant to the geoengineering strategy of injecting stratospheric sulphate aerosols in an attempt to offset greenhouse gas warming. The Program for Climate Model Diagnosis and Intercomparison (PCMDI) has consented to archive results from these experiments, so they can be openly studied. The codes G1, G2, G3, and G4 refer to the four simulations conducted in the suite of experiments. In particular, G1, G2, and G3 are designed to produce an annual mean global radiative balance at the top of the atmosphere.

Experiment G3 is more realistic than the other three, in the sense that it provides a scenario of possible implementation of stratospheric geoengineering (see Fig.(2.1)). It assumes an RCP 4.5 scenario (representative concentration pathway, with a radiative forcing of 4.5 W m^{-2} in the year 2100, see above), but with additional stratospheric aerosol added starting in the year 2020, which is a reasonable estimate of when the delivery systems needed to inject the aerosols might be ready, and stopped in the year 2070[5]. Stratospheric aerosols are imagined to be added gradually, balancing the anthropogenic forcing to keep the planetary temperature nearly constant. The aim of this experiment is to achieve an ongoing radiative balance, which will likely require differing amounts of aerosol, with a time-varying size distribution. Ideally, the type-G3 models will create, grow, and transport sulphate aerosols from an equatorial injection of SO_2. If a model does not have this capability, aerosols can be added at the Equator or globally in a way similar to each models treatment of volcanic aerosols. If the model is capable, inclusion of O_3 chemistry or the carbon cycle, as well as the relevant couplings with the physical climate system, will allow additional scientific issues to be addressed.

The radiative forcing due to anthropogenic greenhouse gases and aerosols has already been estimated in preparing the RCP 4.5 runs. Therefore, in the G3 simulations, this forcing simply needs to be balanced by aerosol forcing.

2.2.1 BADC Archive and CDO Tool

All the data used in this thesis work have been downloaded from the CEDA archive held by the British Atmospheric Data Centre, BADC. The role of the NCAS (NERC Centres for Atmospheric Science) BADC is to assist researchers to locate, access and interpret atmospheric data and to ensure the long-term integrity of atmospheric data produced by Natural Environment Research Council, NERC, projects (`https:`

[5]However, as it is quite easy to continue experiments of type G3 for an additional 20 years after a 50-year geoengineering period, this recovery period is always a part of the experiments and analyses.

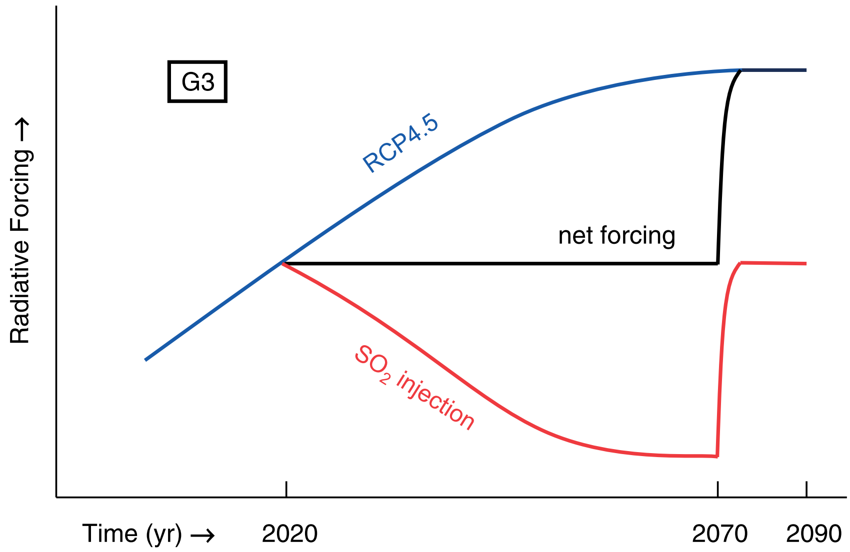


Figure 2.1: Schematic of experiment G3. The experiment approximately balances the positive radiative forcing from the RCP4.5 scenario by an injection of SO2 or sulphate aerosols into the tropical lower stratosphere [Kravitz et al., 2011].

//badc.nerc.ac.uk/). Over the last few years, it has become apparent that the BADC provides services to a wider community than just the atmospheric sciences community (e.g. medicine, biology, waste management, marine sciences, ecology, etc..). CEDA is the Centre for Environmental Data Analysis, whose original group followed the merger of two of NERC's data centres: the BADC and NEODC (the NERC Designated Data Centre for Earth Observation).

The data downloaded from CEDA BADC and worked in this thesis are always in netcdf format and of the type:

$$\mathrm{var_{A}mon_{m}od_{e}xp_{r}unid_{i}nYYYYMM - finYYYYMM.nc}, \tag{2.1}$$

where 'var' is the variable to be analysed (in our case, tas or pr), 'Amon' means monthly mean atmospheric fields (plus some surface fields), 'mod' is the model chosen in the CMIP5 project (in our case, HadGEM2-ES), 'exp' refers to the experiment chosen (for us they are RCP 4.5 or G3), 'runid' identifies the run of the experiment, and 'inYYYYMM-finYYYYMM' stand for initial and final date, respectively (month, M, and year, Y) the data set refers to. Each file analysed contains the variable in terms of longitudes (from 0° to 360°), latitudes (-90° to 90°) and monthly averaged for each year in the range declared in the name of the file itself.

All these files have then been processed through the Climate Data Operator, CDO, (free) tool. CDO is a collection of command line operators to manipulate and analyse climate and numerical weather prediction model data (https://code.zmaw.de/projects/cdo/wiki/cdo).

Chapter 3

Numerical Simulations and Results

We have considered the 70 years of the G3 (GeoMIP) simulations, from December 2019 to December 2089, thus cutting the range on the reference scenario RCP 4.5 (CMIP5) simulations to uniform the comparisons between the corresponding parameters we have chosen to analyse: ‘tas’, the near-surface air temperature (normally, the temperature is reported at the 2 meter height) in Kelvin, and ‘pr’, the total precipitation at surface including both liquid and solid phases from all types of clouds (both large scale and convective), in mm d^{-1}. All the data downloaded from the BADC archive (see Ch.(2)) are of type ‘Amon’, meaning monthly mean atmospheric fields (plus some surface fields).

We have firstly studied the behaviour of mean tas and pr parameters over the entire globe and over the 70 year entire time period, both annually and seasonally.

Then, we have focused our attention on the indian region, especially focusing on the summer monsoon season (June-July-August, JJA) with respect to the winter December-January-February, DJF, season. Finally, we have studied what happens to India average temperature and precipitation in the very period soon after the geo-engineering switch-on, i.e. the 40 year time period going from 2030 to 2070. Note that we have chosen the starting year not to coincide with the real switch-on year, but 10 years later: this is because we have assumed the 10 years 2020-2030 as a period of adjustment.

3.1 Global Scale

3.1.1 Annual

The surface air temperature changes for the G3 runs as compared to the mean of the control run are shown in Fig.(3.1). In this picture we see that all the Northern

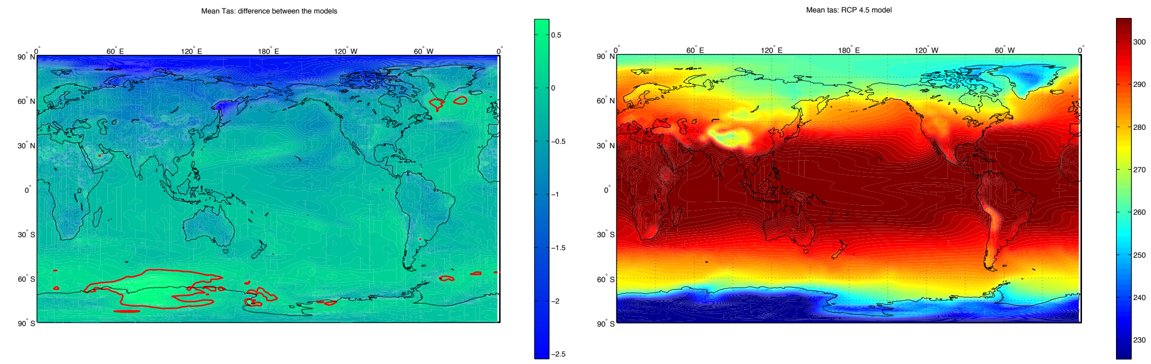


Figure 3.1: Global annual mean tas in K on the period 2020-2090. The red line represents hereafter a zero-value difference. 1a: Difference between the G3 geoengineered model and the reference RCP 4.5 model; 1b: The RCP 4.5 model.

Hemisphere (NH) and almost all the South Hemisphere (SH), except for an Antarctic zone and a zone in the North-Atlantic, are cooler in G3 with respect to the reference scenario RCP 4.5, as desired. And this happens more dramatically on land. That is in perfect agreement to the known simulations in literature [Rasch et al., 2008]. This cooling is remarkable in the Arctic: it is about 2.5 °C colder in G3 than in RCP 4.5, thus alleviating the so-called 'Arctic amplification' phenomenon[1]. The positive difference in the Antarctic instead may be due to changes in the se-ice over oceans. In a nutshell, tropical injection schemes such as G3 could cool the global average climate. There would be more cooling over continental areas, as expected. Thus the consequences for the African and Asian summer monsoons could be serious, threatening the food and water supplies to billions of people.

Annual average changes in precipitation are very small in percentage, as expected [Yang et al., 2003]: from a maximum of 0.3 mm d^{-1} increase of rainfall in a geoengineered world vs. 4 mm d^{-1} foreseen by RCP 4.5 in the southern Pacific, to a minimum of -0.4 mm d^{-1} reached across the Intertropical Convergence Zone (ITCZ)[2], where we have less precipitations (consistent with a colder world) than in a business-as-usual scenario that foresees an average value of about 10 mm d^{-1}. Moreover, the

[1] The warming trend in the Arctic is almost twice as large as the global average in recent decades [IPCC, 2013]. This is known as the 'Arctic amplification'. Changes in cloud cover, increases in atmospheric water vapour, more atmospheric heat transport from lower latitudes and declining sea ice have all been suggested as contributing factors. The actual knowledge seems to pinpoint the major cause of the enormous Arctic warming in the declining of the sea ice [Screen & Simmonds, 2010].

[2] The Inter-Tropical Convergence Zone, ITCZ, appears as a band of clouds consisting of showers, with occasional thunderstorms, that encircles the globe near the equator. It exists because of the convergence of the trade winds: very roughly speaking, in the northern hemisphere the north-east trade winds converge with south-east winds from the Southern Hemisphere. The point at which the trade winds converge forces the air up into the atmosphere, forming the ITCZ.

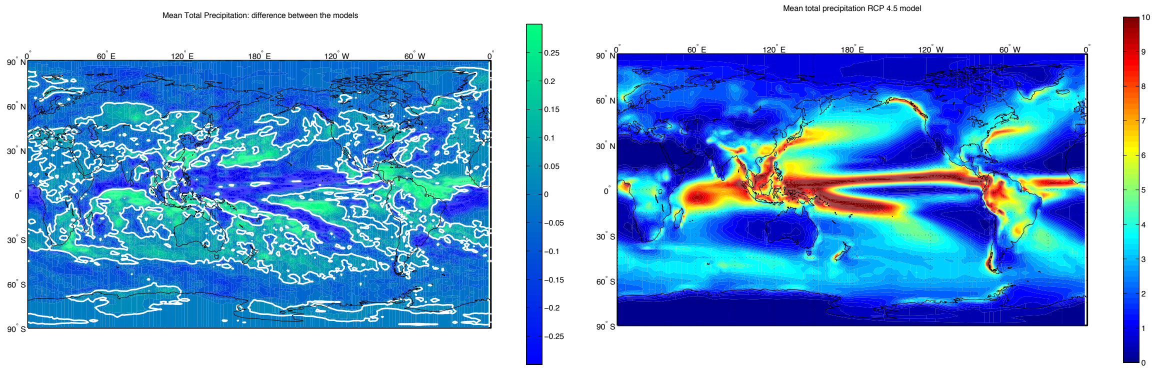


Figure 3.2: Global annual mean pr in mm d^{-1} on the period 2020/2090. The white line represents hereafter a zero-value difference. 2a: Difference between the G3 geoengineered model and the reference RCP 4.5 model; 2b: The RCP 4.5 model.

G3 northern Pacific will be almost less rainy than its RCP 4.5 forecast. The same happens for the northern Indian Ocean and the north-west Atlantic Ocean, while for the south Indian Ocean and the north-east Atlantic Ocean there will be an increase of precipitations. For the south Atlantic, the G3 runs foresee less rain. Generally, all the equatorial strip is characterised by a net (by the way little) decrement of the rainfalls of about 0.25 mm d^{-1}. It is remarkable that the zone including Australia, characterised by an nearly total absence of precipitation, is interested by a sensible augment of rainfall quantifiable around 20%. Note also the 15% increase on North-Africa, less marked on the extreme south; while there is a general diminishing of the rain both on the equatorial Africa and on India, Russia and all Europe, except from almost all Italy.

Thus, while the global average air surface temperature is almost globally reduced, for the total precipitation the question is far more tricky and surely deserves much more insight, especially for the aftermaths on the lives of billions and despite the difficulty related to the studies on this very peculiar climatic parameter that is the precipitation.

If we look at the standard deviations pertaining the annual means of the climatic parameters at stake, Figg.(3.3), we find that the tas interannual variability for G3 results slightly larger than the reference scenario on the Arctic, and on-land on most of Russia, China, Alaska and Canada (max of 0.3 K out of the 15 K on Russia and Canada, while 0.3 K out of 10 K on the Arctic). Note that almost the entire tropical and sub-trobical strip, zones of roughly zero standard deviation for the RCP 4.5 model, is characterised by a visible 15% decrement of the interannual variability in G3; whereas the Antarctic continent sees a strong interannual variability of about 15 K for the reference scenario and a slightly less (0.3 K) variability for the geoengineered scenario. Of course, the situation for the precipitation parameter is

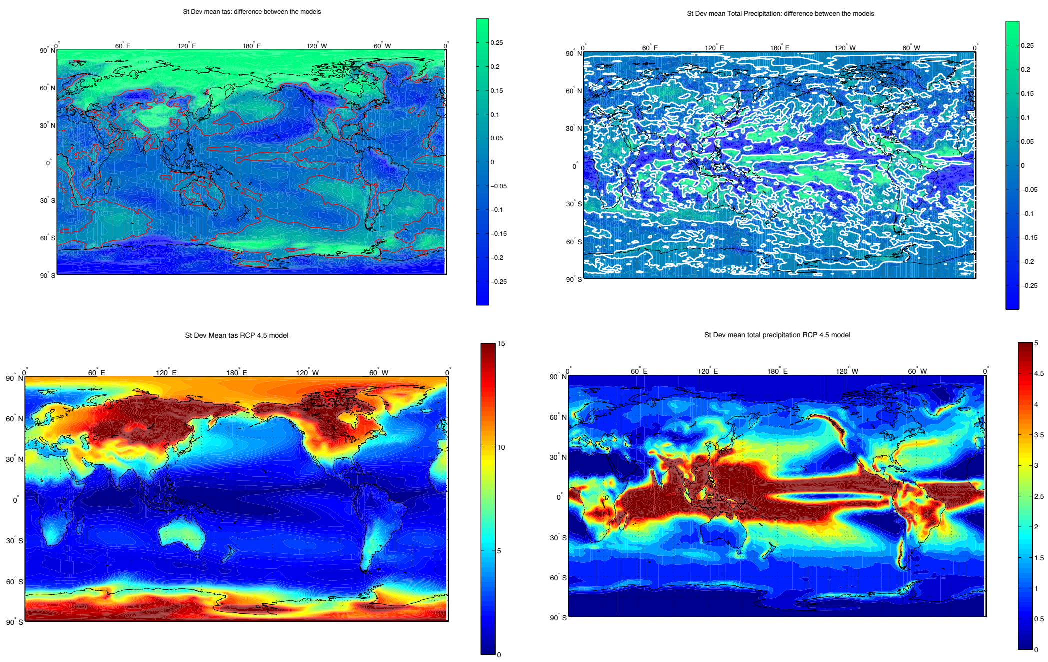


Figure 3.3: 3a: Standard deviation tas in K: difference between G3 and RCP 4.5 in the period 2020/2090; 3b: Standard deviation pr in mm d^{-1}: difference between G3 and RCP 4.5 in the period 2020/2090; 3c: Standard deviation tas in K for the RCP 4.5 model; 3d: Standard deviation pr in mm d^{-1} for the RCP 4.5 model.

a bit more complex and structured, but the difference between the models always remains slight. What can be immediately deduced is a neat 25% amplification of the interannual variability in G3 for North-Africa and the majority of Australia. The ITCZ, on the contrary, sees a diminishing of variability, from the maximum of 7 mm d^{-1} for the RCP 4.5 to a decrease of about 4% for G3.

Some other important information comes from the global timeseries, Figg.(3.4). From them, we learn that, although still in a contest of global warming (as a matter of fact, we are not diminishing the amount of greenhouse gases), G3 globally reduces both temperature (as expected) and precipitation (as a consequence for the reduced temperature). For temperature, there is a maximum difference characterised by a decrease of about 1 K around the year 2059 (that is, exactly the amount of growth we have reached today with respect to the pre-industrial age). Whereas, for precipitation one finds a decrease[3] of 0.1 mm d^{-1}. Of course, both the decrements are more stronger in the period 2030/2070 where the world becomes geoengineered by the sulphates. Most important is to note that soon after the SO_2 injection switch-

[3]The fact that both temperature and precipitation join their respective minima in the same years is consistent with the gross consideration that the lower the temperature, the lower is the quantity of water vapour in the atmosphere and the lower is the quantity of rainfall, globally.

off, after some 3-5 years of transient situation, both temperature and precipitations pop up again rendering the situation quite unbearable, as there is very little time for adaptation to the new harsh climate conditions.

It is clear from our results that in a proper geoengineered scenario, the planet would be cooler and thus the global warming, in a context where primarily mitigation and adaptation actions are deployed, could be reversed[4]. Figure (3.1) shows that if enough SO_2 could be continuously injected into the stratosphere, the global thermostat could be adjusted at any setting. This opens a big conundrum because if stopped at some time, say by lack of technical capability, political will, or discovery of unforeseen negative consequences, there would be even more rapid global warming than has occurred in the past century or than is projected with business-as-usual, as previously shown by Wigley (2006) and Matthews and Caldeira (2007). Adaptation to such a rapid climate change would be very difficult.

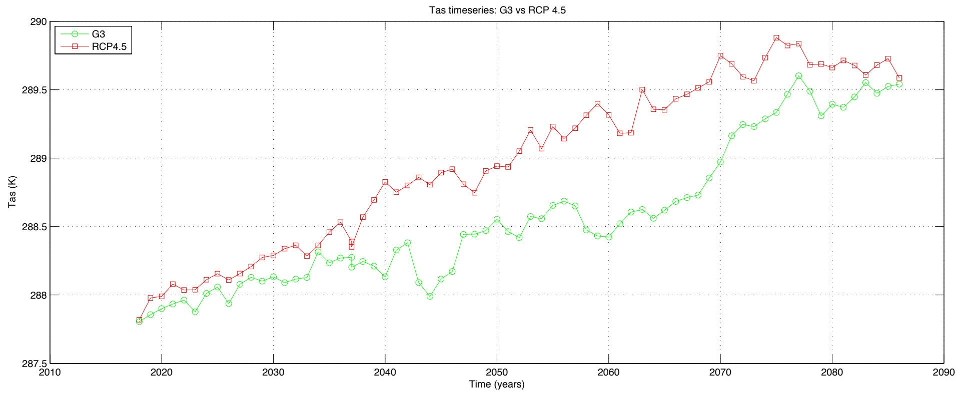
Still, many of the perturbations are much smaller than those evident in an 'ungeoengineered world' with CO_2 warming. A fundamental example concerning this issue concerns the South Asia Monsoon Region (SAMR): both models show changes in the Indian and south-east Asian monsoon regions, but the perturbations after geoengineering are smaller than those without geoengineering and are less than or equal to 0. 5 K for temperature and 0.3 mm d^{-1} for precipitation in an area where seasonal precipitation rates reach 6-15 mm d^{-1}. Moreover, it is important to stress that monsoons are a notoriously very difficult phenomenon to model [Annamalai, 2007]. These caveats only serve to remind about the importance of a careful assessment of the consequences of geoengineering, and the general uncertainties of modelling precipitation distributions in the context of climate change.

3.1.2 Seasonal

Some more insight on the climate can be obtained through the analysis of the seasonal timeseries.

Starting with the timeseries of the near-surface air temperature, Figg.(3.5), by a comparison among the four we find at a glance that the greatest variability is in the DJF season. In this context, with variability we mean the difference between the value foreseen by the reference scenario for a certain year and the corresponding one by the geoengineered model. More precisely, a 1.3 K in DJF for the year 2060; 0.8 K in MAM season for the years 2040, 2044 and 2060; 0.8 K in JJA for years

[4]This brings up some basic questions of what the optimal global climate should be, if we could control it: it should be the current climate or the preindustrial climate, or whatever one decides. And then, who would decide?



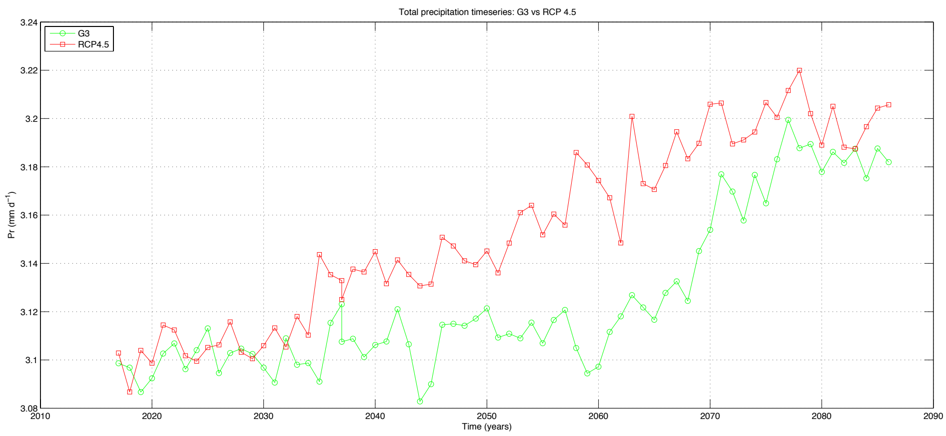


Figure 3.4: 4a: Tas timeseries: G3 vs RCP 4.5; 4b: Pr timeseries: G3 vs RCP 4.5.

2040 and 2059; 1.1 K in SON for the year 2059. Moreover, we see that seasons DJF and MAM are similar; also, seasons JJA and SON are similar. Note that, of course, the geoengineered world always results cooler and the maximum variability between the models is found in the period 2030/2070 when the sulphates are thrown in the stratosphere. As we expected, before this period, the two curves are almost identical (except for slight differences); while soon after 2070, when the SO_2 injection is switched off, the G3 world temperature immediately rushes up to the un-healed world.

The G3 model, as shown in Figg.(3.6), certainly sees a cooling of the Arctic, especially in DJF, MAM and SON, when we have a decrease of at least 2 K that directly reflects in preventing Arctic sea ice melting. The situation is not so good in the Boreal summer season, JJA, when we are faced with an additional augment of most of the North Pole temperature of about 0.5 K. By the way, the seasonal forcing is the largest in the winter hemisphere (that is, Boreal hemisphere in DJF, and the Austral hemisphere in JJA). From the maps we also discover a general decrease of the temperatures on lands, except for Antartica where there is a slight raise of 0.2-0.3 k over the RCP 4.5 220 K, above all near the coasts in DJF, MAM and SON followed by an almost total increase of 0.5 K in the JJA season. Figg.(3.6) thus confirm the general behaviour found in the tas seasonal timeseries, Figg.(3.5).

As for the interannual seasonal variability of the two models, Figg.(3.7), we see that there is almost no seasonal difference along the equatorial and sub-equatorials strip, where the G3 scenario is characterised by a lower standard deviation w.r.t. the RCP 4.5 one. The situation changes in correspondence of the Poles. For Arctic, we have a higher variability for G3 in SON, MAM and partially in JJA; whereas, it is lower in DJF. For Antarctic, G3 interannual variability is almost generally higher than RCP 4.5.

Considering the fact that seasons DJF and MAM on a side, and JJA and SON on the other, show similar behaviours with only slight differences, we have decided to focus on the two extreme seasons hereafter: DJF and JJA. This also in view, as we shall demonstrate in the next section, of the fact that they are these two seasons to deeply mark the Indian monsoon.

From the total precipitation global maps, Figg.(3.9), we can deduce that there are at least three situations deserving attention: the G3 sensible raise in rainfalls in both seasons on Oceania (which passes from a 0 to some 0.3-0.4 mm d^{-1}), the increase of precipitations on on North Africa, and the very peculiar situation of India. More precisely, in DJF G3 foresees an augment in rainfall equal to about 0.2-0.3 mm d^{-1} on south-east and north-west (as well as the Tibetan Plateau); whereas in JJA, there is a decrease in precipitation of about 0.5 mm d^{-1}. These two projections are

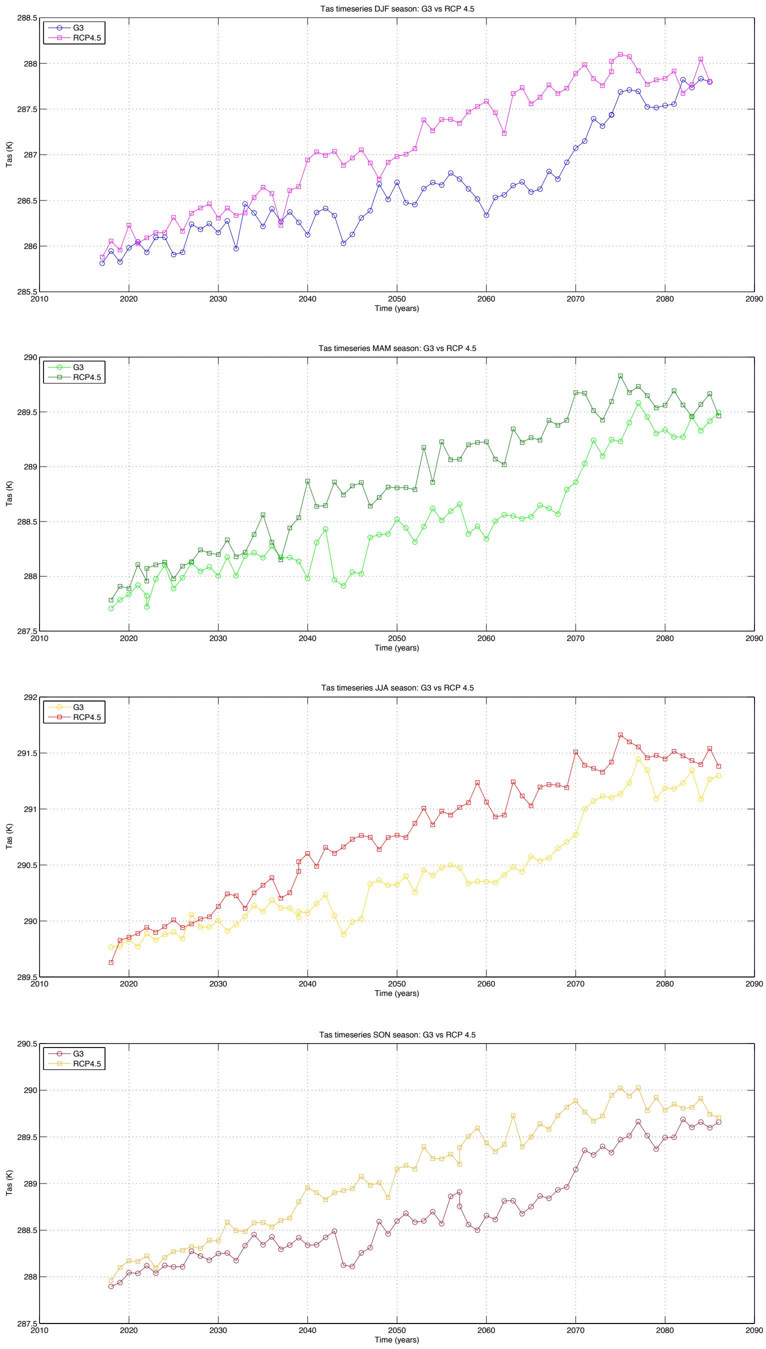


Figure 3.5: Tas seasonal timeseries, years 2020/2090, G3 vs RCP 4.5. 5a: DJF; 5b: MAM; 5c: JJA; 5d: SON.

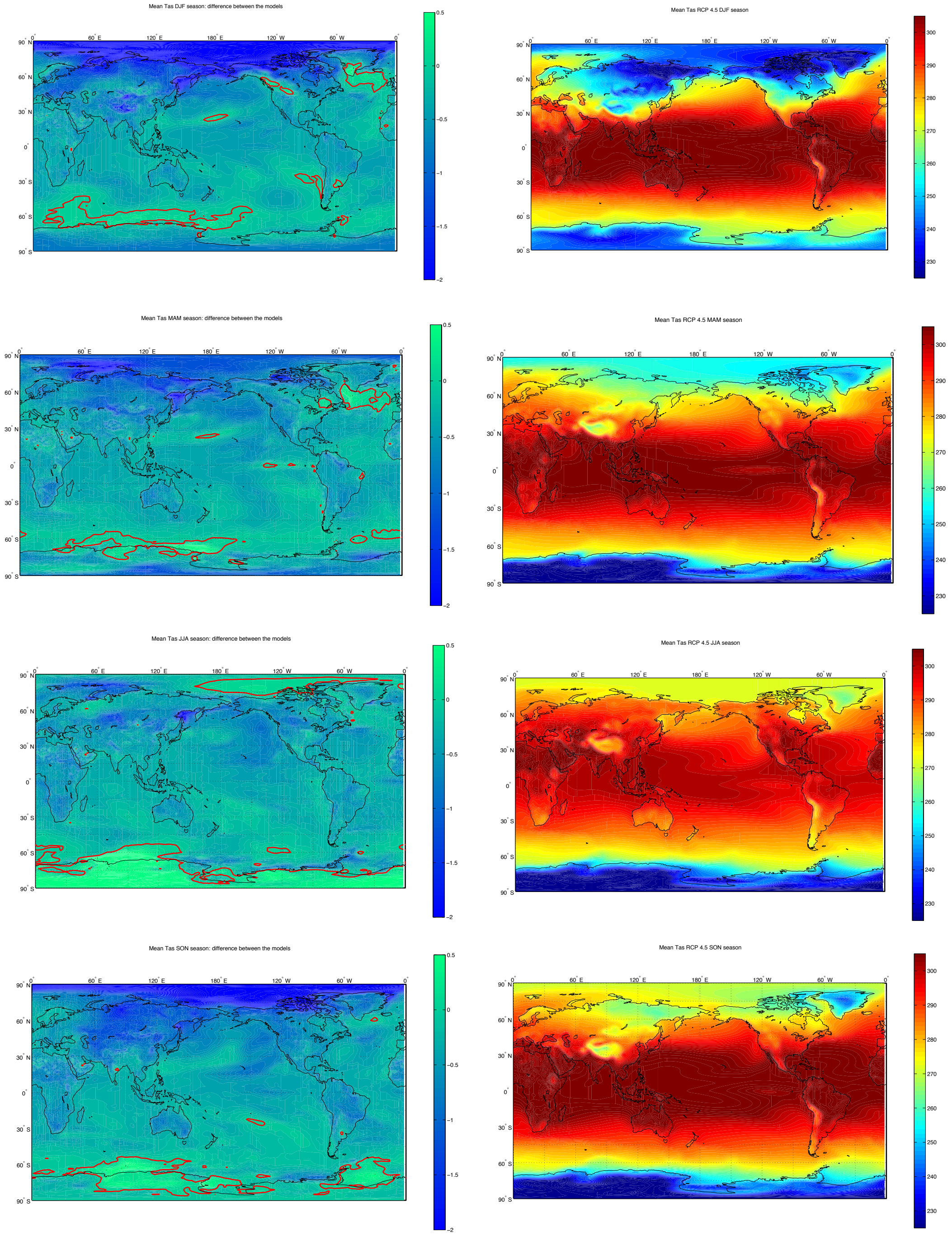


Figure 3.6: Tas seasonal means in K, years 2020/2090. 6a,c,e,g: Differences between the models G3 and RCP 4.5 in season DJF, MAM, JJA and SON, respectively; 6b,d,f,h: the reference scenario RCP 4.5 in seasons DJF, MAM, JJA and SON, respectively.

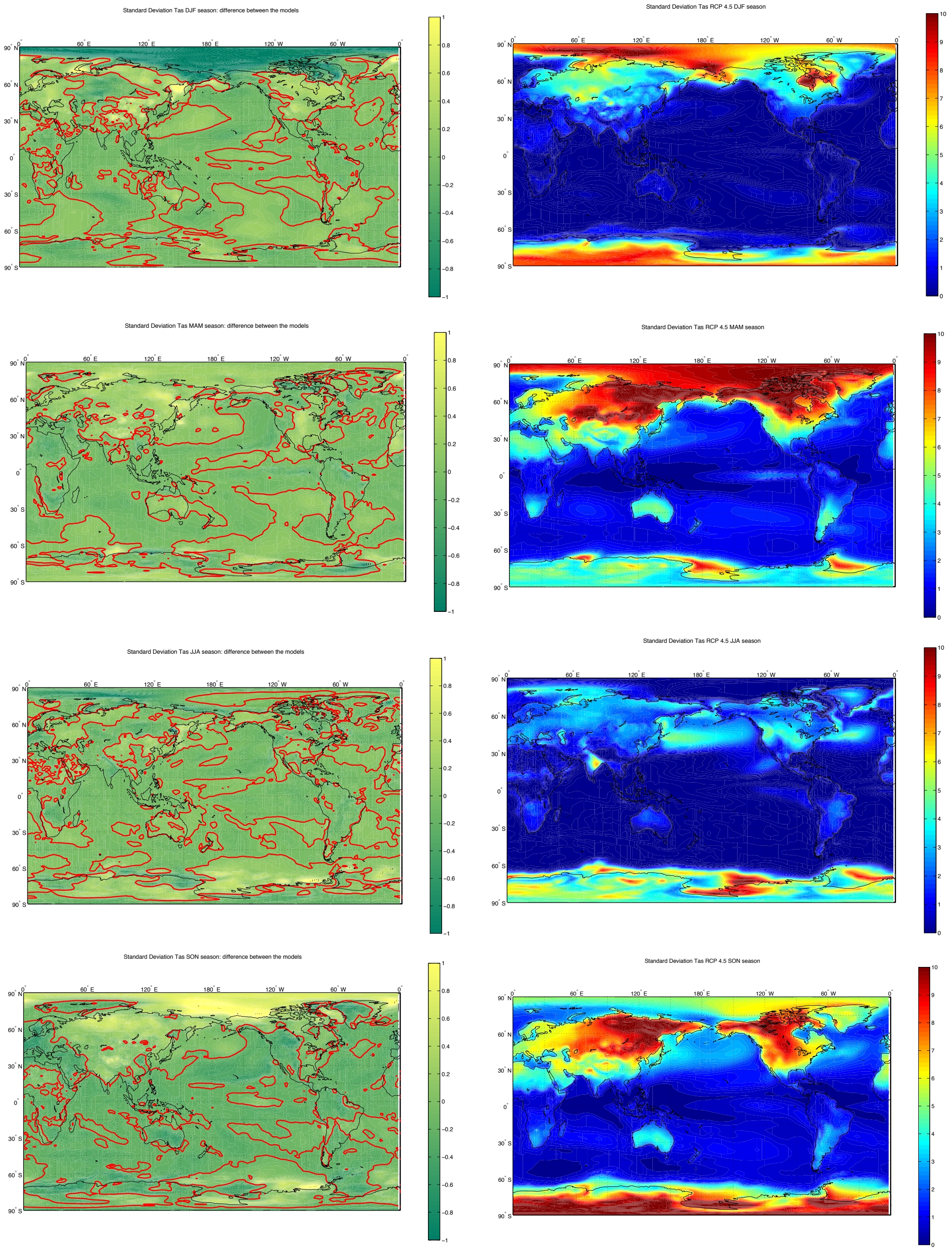


Figure 3.7: Standard deviation tas seasonal means in K, years 2020/2090. 7a,c,e,g: Differences between the models G3 and RCP 4.5 in season DJF, MAM, JJA and SON, respectively; 7b,d,f,h: the reference scenario RCP 4.5 in seasons DJF, MAM, JJA and SON, respectively.

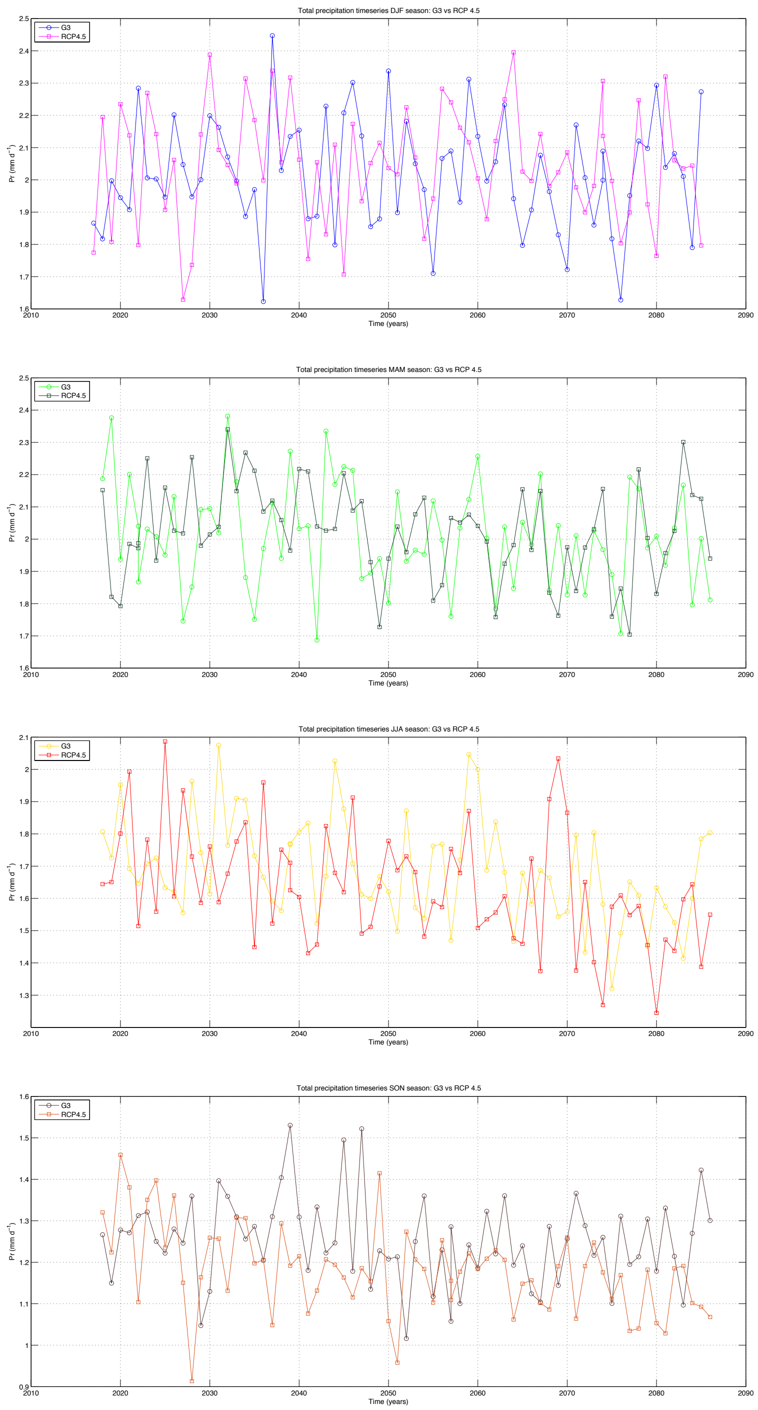


Figure 3.8: Pr seasonal timeseries, years 2020/2090, G3 vs RCP 4.5. 8a: DJF; 8b: MAM; 8c: JJA; 8d: SON.

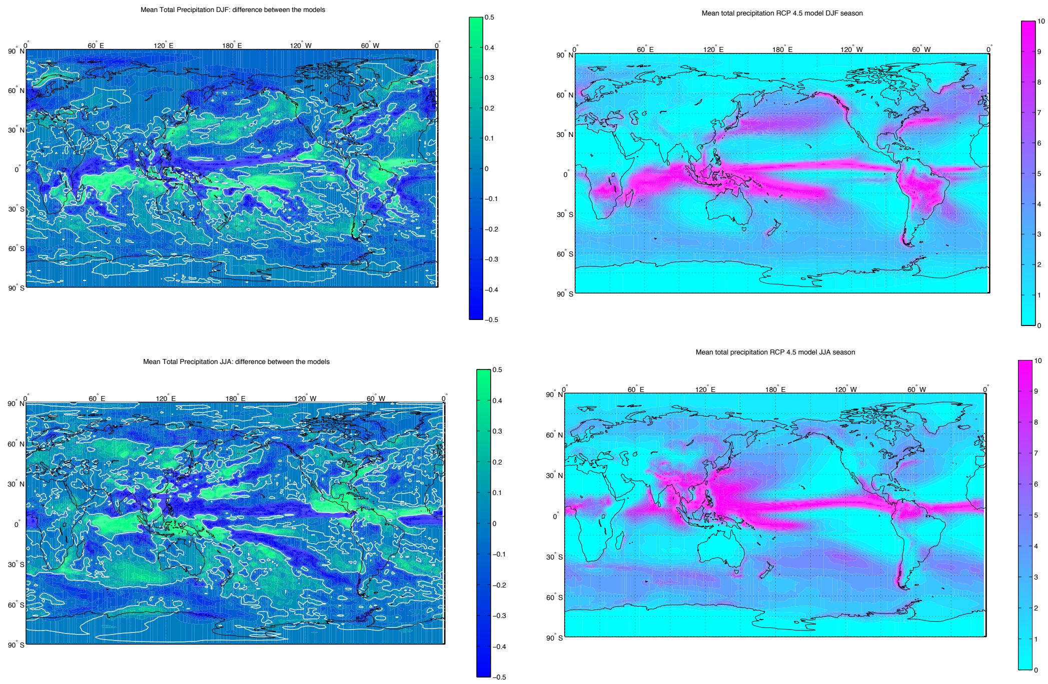


Figure 3.9: Pr seasonal means in mm d^{-1}, years 2020/2090. 9a,c,: Differences between the models G3 and RCP 4.5 in season DJF and JJA, respectively; 9b,d: the reference scenario RCP 4.5 in seasons DJF and JJA, respectively.

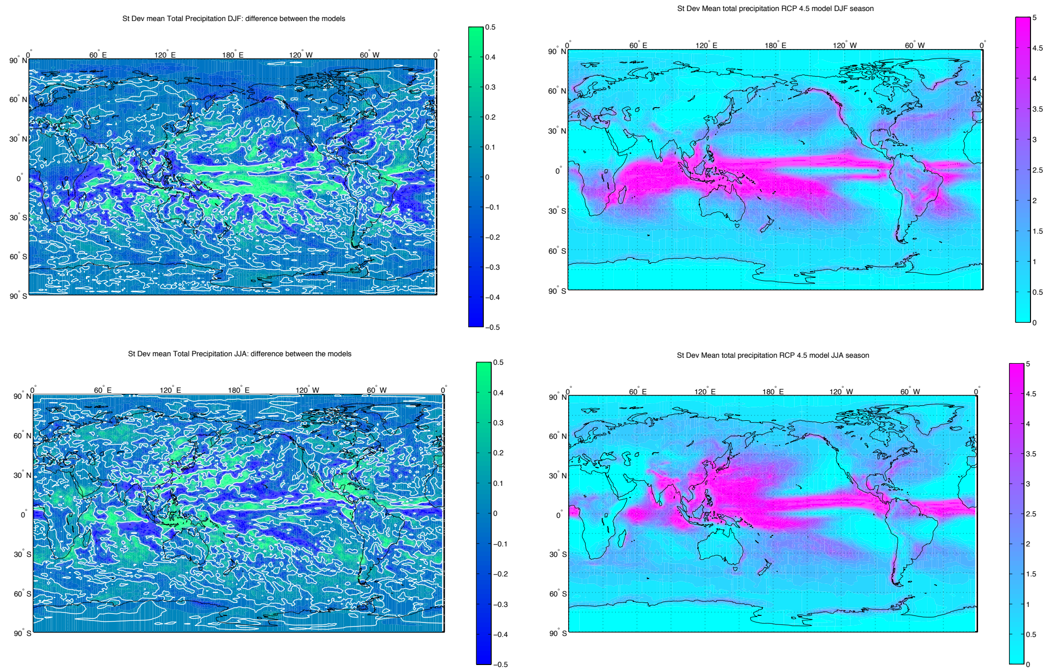


Figure 3.10: Standard deviation pr seasonal means in mm d^{-1}, years 2020/2090. 10a,c: Differences between the models G3 and RCP 4.5 in season DJF and JJA, respectively; 10b,d: the reference scenario RCP 4.5 in seasons DJF and JJA, respectively.

very serious and dangerous: if this was the case, there would be serious upheavals to the Indian (and more generally to the entire South Asia monsoon) monsoons. The consequences on at least the lives of a billion Indians would be hardly threatened.

Figg.(3.10) describe more interannual seasonal variability along the ITC zone, most of India (above all in DJF), most of Oceania and most of the Antartica in both seasons. Instead, the decrease of the variability on-land on the equatorial and Southern Africa in DJF (with a slight raise of variability, in contrast, in the North) is followed by a quite diffuse increase in JJA.

To end this paragraph, we show the trends of both temperature (in K y^{-1}) and precipitation (in mm d^{-1} y^{-1}) for the seasons DJF and JJA cut for the period of sulphate injection 2030/2070, Figg.(3.11) and Figg.(3.12) respectively. From Figg.(3.11) we can infer that the large positive trend in DJF in tas over Arctic is much alleviated in G3 as well as trends over land in NH. JJA trends are almost the same but somehow on land, in addition to the Arctic.

On the other side, the pictures depicting seasonal precipitation trends, Figg.(3.12), show smaller trends over continents for G3 in DJF and more pronounced differences

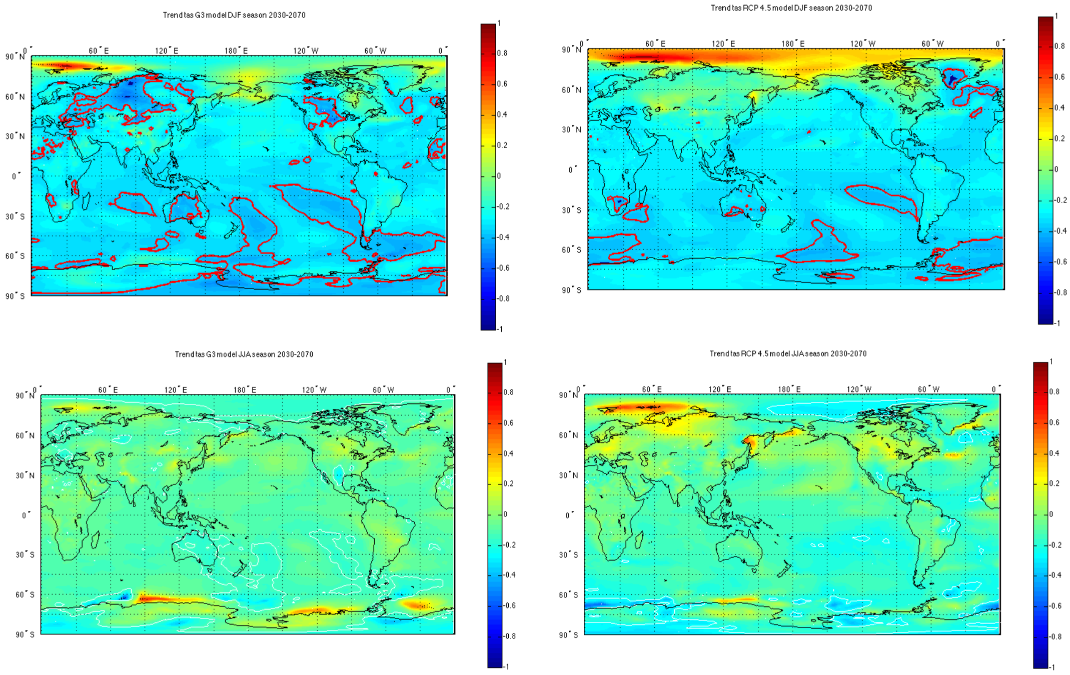


Figure 3.11: Trend tas in K y^{-1} for DJF (zero-line in red) and JJA (zero-line in white) season. 11a,c: G3 model; 11b,d: RCP 4.5 model.

at equator in JJA.

Resuming in a nutshell what stated above, we can conclude that, if enough sulphates were injected in the stratosphere so to realise the G3 scenario, then while Arctic temperature could be controlled, and sea ice melting could be reversed, there would still be large consequences for the summer monsoons, mostly on South Asia and above all on India.

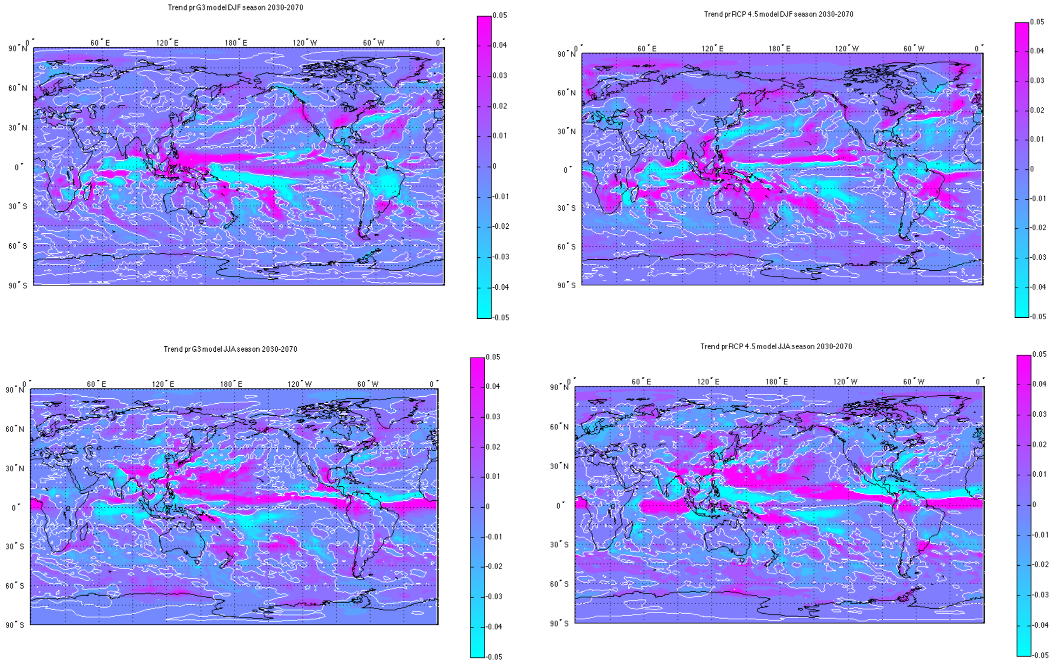


Figure 3.12: Trend pr in mm d^{-1} y^{-1} for DJF and JJA season. 11a,c: G3 model; 11b,d: RCP 4.5 model.

Chapter 4

The Focus on India

We have seen in the previous chapter that, although it is possible to cool the Earth, thus slowing down the surface temperature increase, not only it is not likely that all aspects of the physical system will linearly respond returning to a state such as that prior to the large human-induced CO_2 increases, but also the regional changes could be very different from the global scale and to a considerable extent catastrophic. Among the regional situations that gain most concern there is surely India. This is not only because of the aftermaths of a possible future deployment of a geeingneering method on socio-economic, political, agricultural, water and food supply aspects for its enormous population (nowadays, about 1.2 billion people); but also for the global consequences that could follow a twisting of the summer Indian monsoon, given its relations with other fundamental global phenomena.

4.1 The Indian Summer Monsoon in a Nutshell

The Indian summer monsoon provides 75% to 90% of the total annual rainfall over the country during the four months June to September and is vital to the national economy. Food production, power generation and drinking water supply are all dependent on the monsoon rainfall, which has crucial control on the national economy [Webster et al., 1998]. Owing to the great socio-economic importance of the fluctuation of the Indian monsoon rainfall, there is the urgent need of forecasting the possible aftermaths on it following the deployment of a geoengineered scenario on this land.

Roughly speaking, the monsoon season is the wind system over India and adjoining oceanic regions that blows from the south-west half the year and from the northeast during the other half. The seasonal reversal of the wind direction, associated with the surface temperature contrast between the Indian continent and the Indian Ocean, occurring during April/May brings copious moisture from the warm waters of the tropical ocean to the Indian continent through south-westerlies. Most of the annual rainfall in India occurs from June to September, during what is referred to as the 'Summer Monsoon', SM, (or 'south-west monsoon'). It is for this reason that we have chosen to study the aftermath of a geoengineered scenario on India focusing on this very season in contrast to the winter season DJF.

Of course, there is also a 'winter monsoon' (or 'north-east monsoon): it brings rainfall to the south-eastern part of India through north-easterlies during October to December and contributes a small percentage to the annual Indian rainfall.

Two remarkable features of the summer monsoon are its regular occurrence every year from June to September and the irregular variation in the amount of seasonal mean rainfall that it brings to India from one year to the other. In fact, there are many instances of years with flood (strong monsoon) or drought (weak monsoon) during which India as a whole receives excess or deficient seasonal rainfall, respectively. Even within a season, there is considerable variation, both in space and time, in the rainfall over India. To this extent, one can speak of an intraseasonal variation, characterised by active periods of high rainfall and break periods[1]. with weak or no rainfall over central India and the west coast (each phase lasting for a few days) and an interannual variability of the summer monsoon[2]. Those variabilities have a tremendous socio-economic impact on India, especially in the fields of agriculture and health.

The Indian monsoon is a global phenomenon involving, and strictly depending to, other phenomena like the El Niño/La Niña Southern Oscillation, ENSO. With similar connections with the Indian Ocean, Eurasian snow and the climate of other parts of the globe, the Indian monsoon is now understood to be an integral part of the global climate system involving coupled atmosphere-land-ocean interactions [Webster et al., 1998]. Thus, the prediction of the monsoon rainfall and circulation is not only crucial for India but also definitely important for other parts of the globe because of the monsoons relation with such components. With advances made in dynamical prediction of weather and seasonal climate using Global Climate Models (GCMs), the simulation of monsoon by GCMs, and above all its potential predictability [Charney & Shukla, 1981], is an active area of research.

As a matter of fact, the summer Indian monsoon exhibits a huge physical complexity, that goes beyond the scopes of this work. For a more detailed description of it, we refer to [Turner & Annamalai, 2012], and references therein.

[1]Both observations and model simulations seem to suggest that many monsoon drought and flood years are associated with El Niño-Southern Oscillation phenomenon [Turner & Annamalai, 2012; Webster et al., 1998], while the monsoon onset and active-break periods are also related to the phase and frequency of the Madden-Julian Oscillation [Wheeler & Hendon, 2004]

[2]As a matter of fact, it is also known that the monsoon exhibits variability even on interdecadal

4.2 Results and Comments from the Analysis of the Data

As stated above, the annual cycle of the Indian monsoon is associated with that of a larger scale climate system that covers India and the tropical Indian and Pacific Oceans and moves from the Northern Hemisphere (NH) to the Southern Hemisphere (SH) and back. The climatological mean near-surface temperature and total rainfall for the June-July-August (JJA) and December-January-February (DJF) seasons of the annual cycle are shown in Figg.(4.1) and Figg.(4.2), respectively. From what concerns tas, Figg.(4.1), we can deduce that there is a general decrease in the mean annual temperature, both in DJF and JJA seasons, for the G3 scenario w.r.t. the un-geoengineered scenario. This results more marked for the north-western part of India in DJF, where a decrement of 0.8-1 K is reached. During the JJA season, the decrease of temperature is slightly less and more marked in the north.

If we skip to the total precipitation projections, Figg.(4.2), our simulations predict an anomalous increase in rainfalls on the southern Arabian sea and, on-land, on the north-east and central India (as well as on Sri-Lanka) in DJF and a decrease elsewhere[3]. This is anomalous in the sense it does not reflect the general decrease in temperatures found, Figg.(4.1) and the well-known dryness characteristic of the winter Indian monsoon. This anomalous increase is even more marked in season JJA if we consider again the Northern-India; while there is a sensible decrease of rainfalls over the central east and coastal south reaching values of 0.7-1 mm d^{-1} less rain over 5-7 mm d^{-1} foreseen by RCP 4.5, that is already a sensible decrease w.r.t. the average pre-industrial 7mm d^{-1} value, and thus consistent with a cooler G3 JJA season w.r.t. RCP 4.5 scenario.

According to the standard scenario, the climatological mean near-surface temperature shows some spatial interannual variability on all India, except for the deep southern part, as one can see in Fig.(4.3b,d). This is especially true in JJA season. Instead, the G3 scenario sees some differences. Starting withe DJF season, we have a general a slight general augment of the variability on north-east and central-west parts, but a decrease on north-west and south. For the JJA season, the geoengineered India would show, according to our simulations, a general diffuse decrease of interannual variability, more marked on the deep south and north-west (10 to 15%), and an increase of about 15% in the interannual variability for the north-east.

The spatial structure of the interannual variations of the Indian rainfall can be

time scales in association with other global climate variables.

[3]As usual, the white/red lines demarcate the borders of positive w.r.t. negative values of the parameter they refer to. That is, they are the ‘zero-line’.

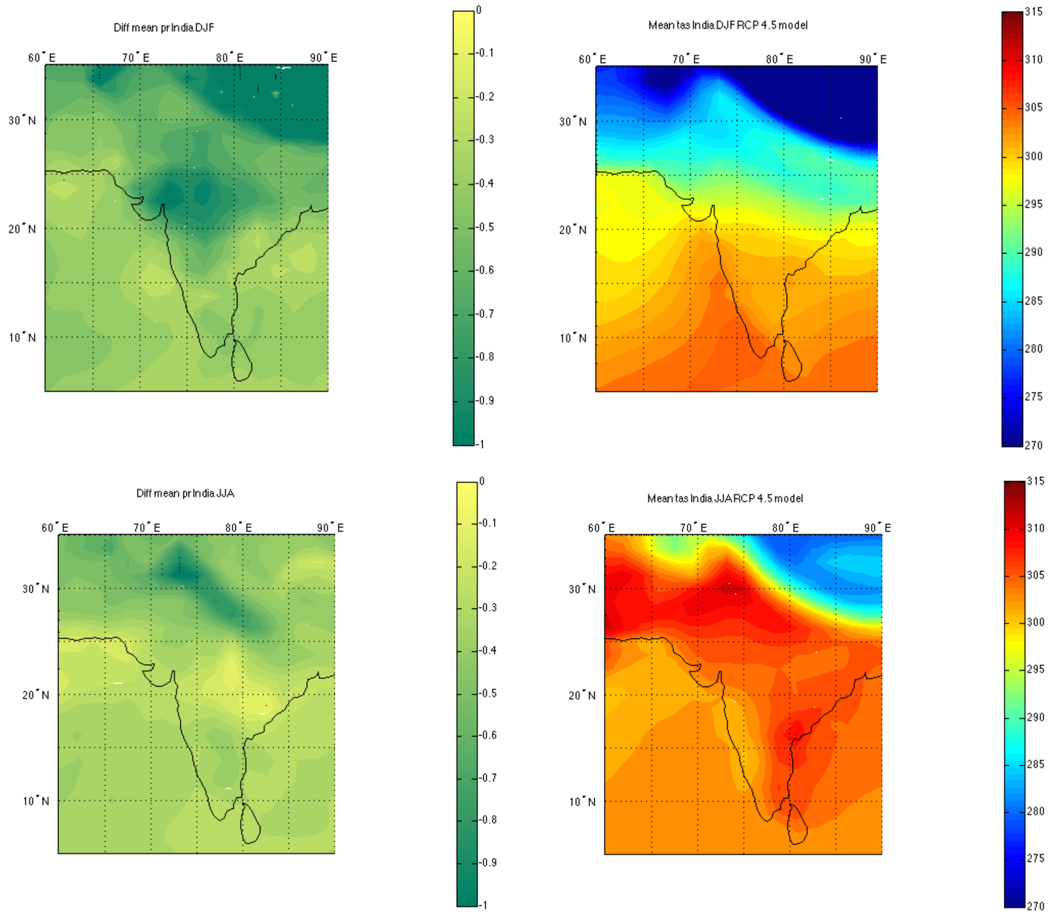


Figure 4.1: Mean tas in K for DJF and JJA season. 13a,c: Differences between G3 and RCP 4.5 models; 13b,d: RCP 4.5 model.

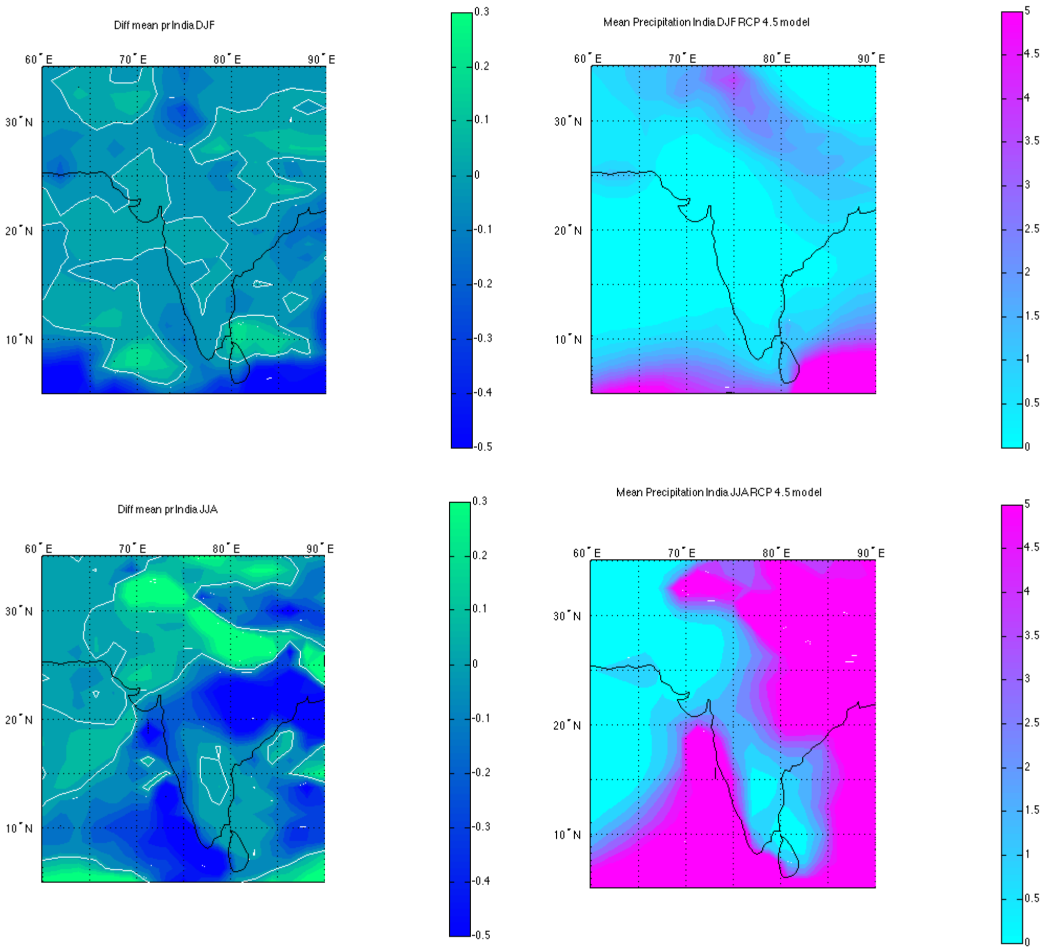


Figure 4.2: Mean pr in mm d^{-1} for DJF and JJA season. 14a,c: Differences between G3 and RCP 4.5 models; 14b,d: RCP 4.5 model.

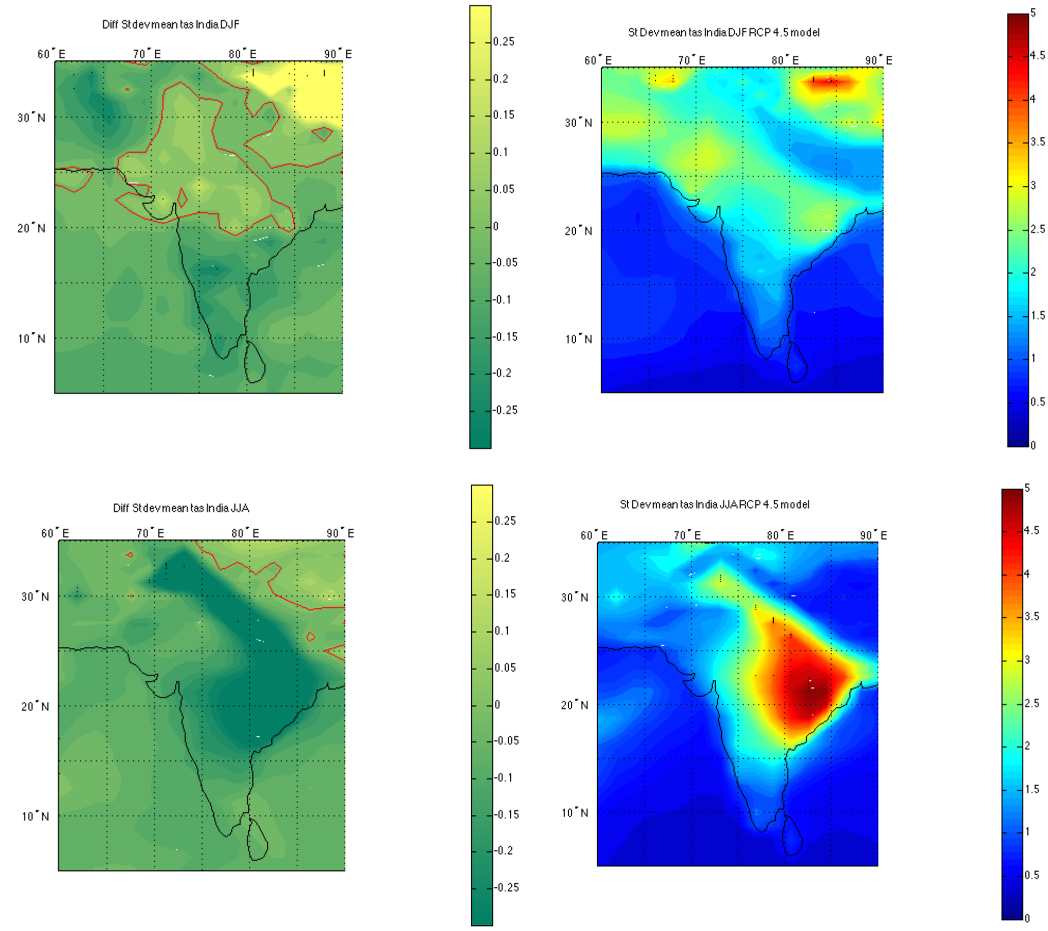


Figure 4.3: Standard deviation tas in K for DJF and JJA season. 15a,c: Differences between G3 and RCP 4.5 models; 15b,d: RCP 4.5 model.

summarised by the maps of the standard deviation for the DJF and JJA seasons, Figg.(4.4). We find that the DJF map shows a net increase of the interannual variability 0f 10 to 30% on almost all the Indian peninsula, except for north-east and the Western Ghats, where the G3 scenario forecasts a decrease of about 20% w.r.t. the RCP 4.5 model. During season JJA the simulations show that central India and the Western Ghats, that have large variability in RCP 4.5, see a slight about 4-5% decrease of it, while on almost the remaining part of India, there is an increase of variability of 10-30%.

Analysing the tas timeseries averaged on the lon-lat cell [60° 90° E, 10° 30° N] Figg.(4.5), we immediately see that there is nearly no remarkable difference between the the behaviour of the two models outside the period of geoengineering deployment (2030/2070) and, inside this period, there is a huge difference between G3 and RCP 4.5 in the period 2050/2070, both in DJF and JJA. In fact, if we zoom in, focusing on the sulphate injection period, we find a single maximum difference of 1.4 K in the year 2035 followed by a series of maxima of about 1.8 K in the period 50/70 for DJF; in JJA, this sensible difference between the two behaviours in the 50/70 period is even more marked, culminating into a 2 K for the year 2069.

The timeseries for precipitation, Figg.(4.6), are characterised by a huge year-to-year variation, for both models and both seasons. This is more marked for DJF, where we can find from a year to the next even a quintuplication of the mean rainfall (e.g., from 2037 to 2038 the RCP 4.5 foresees an increase from 0.2 mm d^{-1} to 0.95 mm d^{-1}), whereas the maximum year-to-year gap during season JJA corresponds to a rough doubling of the rainfall (e.g., 4.6 mm d^{-1} for year 2028 followed by 2.4 mm d^{-1} for 2029 for the RCP 4.5 model)[4]. Because of this very huge variability of the time series, not much more information can be obtained by simply looking at them. That is why the next step is to analyse what happens to tas and pr means by zooming in the period of geoengineering method deployment. Once this is done, if on a side we find no significant new information from tas, Figg.(4.7), on the other much more insight is given by the difference in the pr means,Figg.(4.8): from these, we learn that during the geoengineering switch-on practically all India is more rainy in DJF, whereas all of the peninsula is definitely less rainy in JJA season. It is important to stress that these conclusions are quite different from those obtained by the integration in the entire period and shown in Figg.(4.2), which saw a very jagged situation versus the net one of Figg.(4.8).

As for the standard deviations, that is the interannual variability, the lower variability in tas both in DJF and JJA characterising the G3 model cut for the switch-on period, Figg.(4.9), is contrasted by a widespread DJF higher interannual variability of the G3 model w.r.t. the standard RCP 4.5, Figg.(4.10).

For completeness, we also show the near-surface temperature, Figg.(4.11), and

[4]This is clearer if we plot the probability distribution function of the yearly precipitation (not shown)

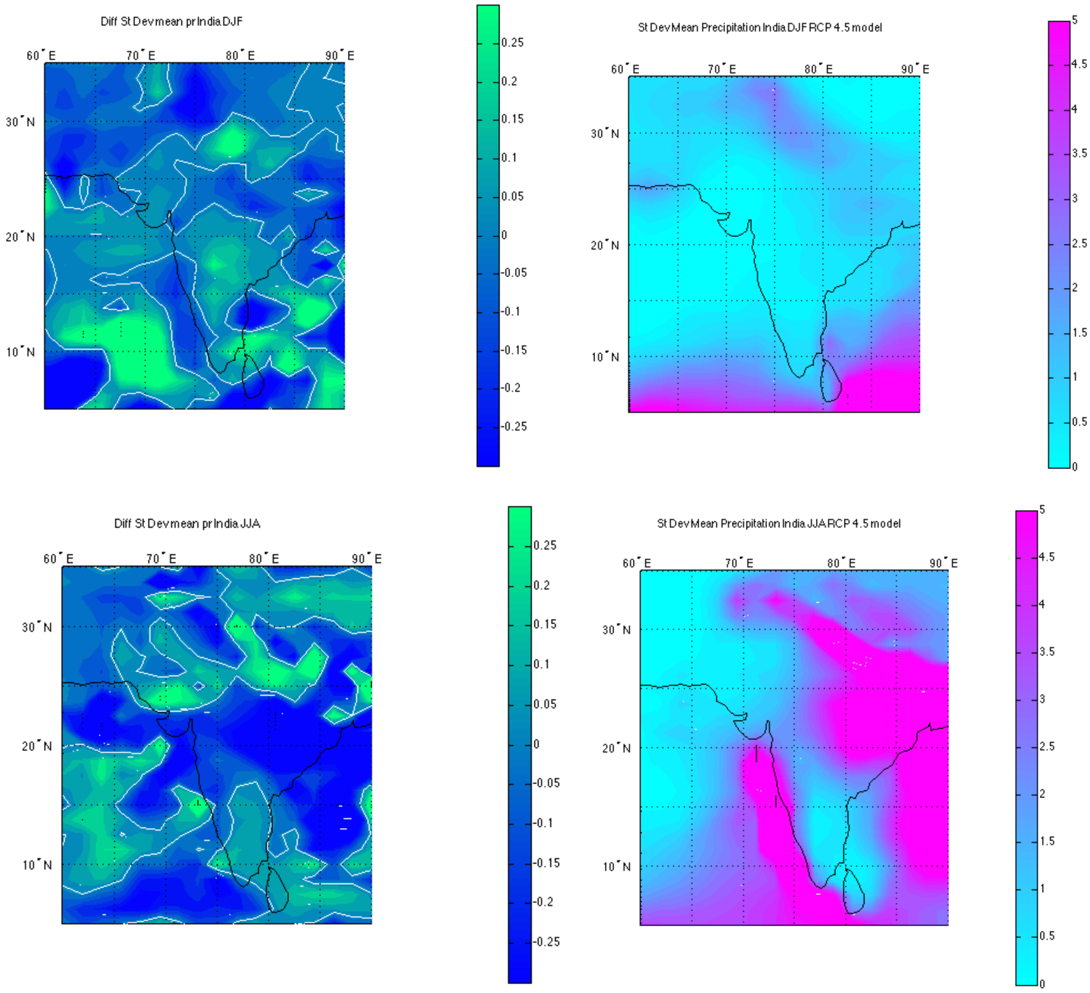


Figure 4.4: Standard deviation pr in mm d^{-1} for DJF and JJA season. 16a,c: Differences between G3 and RCP 4.5 models; 16b,d: RCP 4.5 model.

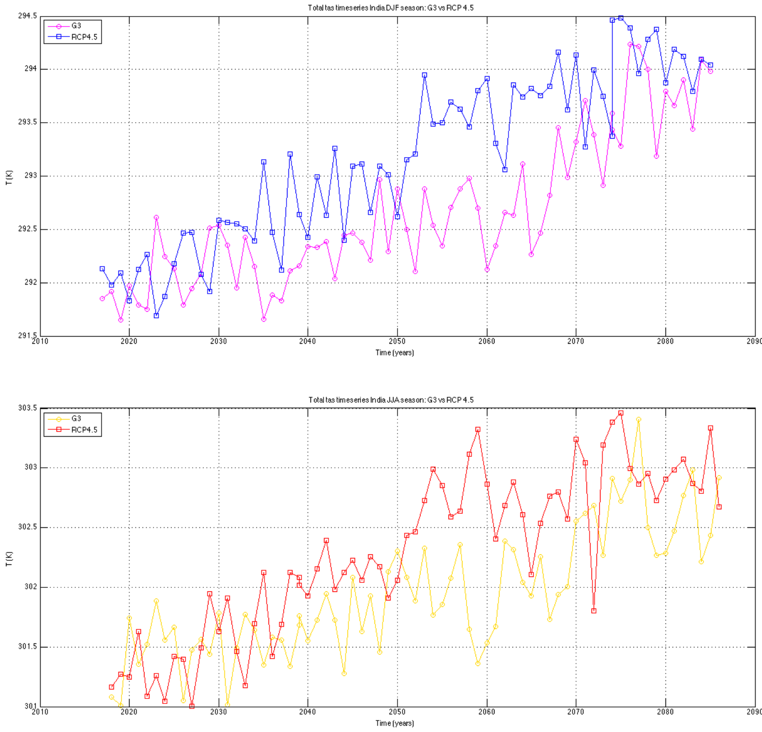


Figure 4.5: Tas timeseries, G3 vs RCP 4.5. 17a: DJF season; 17b: JJa season.

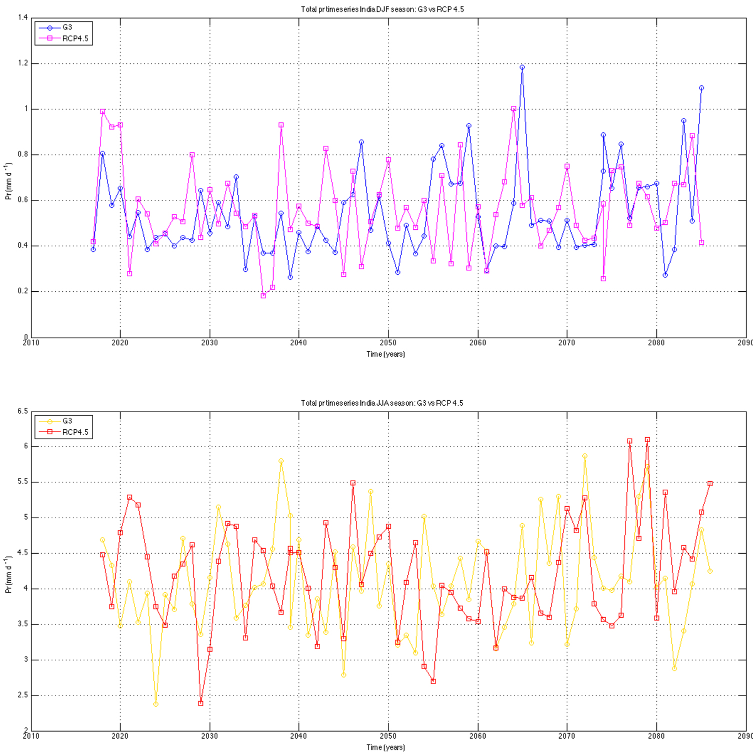


Figure 4.6: Pr timeseries, G3 vs RCP 4.5. 18a: DJF season; 18b: JJA season.

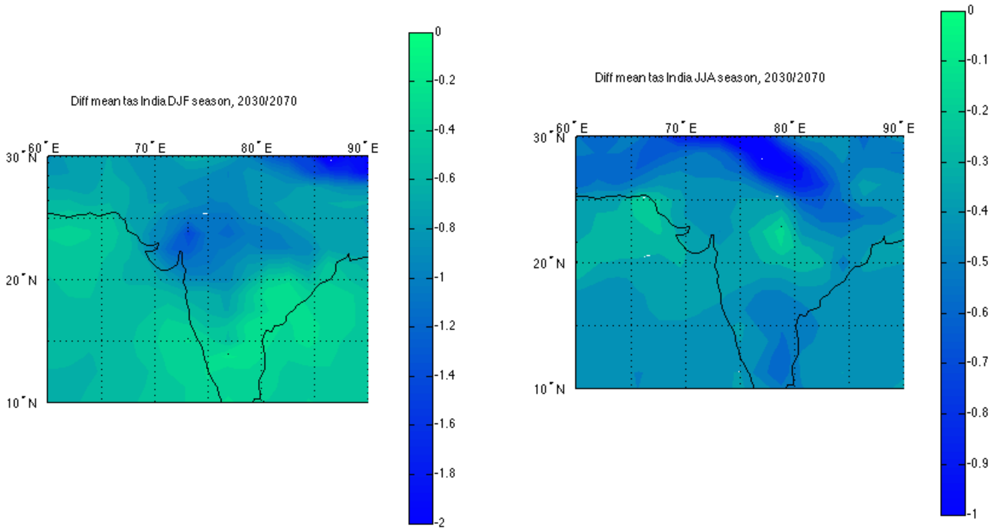


Figure 4.7: Mean tas differences in K for India, period 2030/2070. 19a: DJF season; 19b: JJA season.

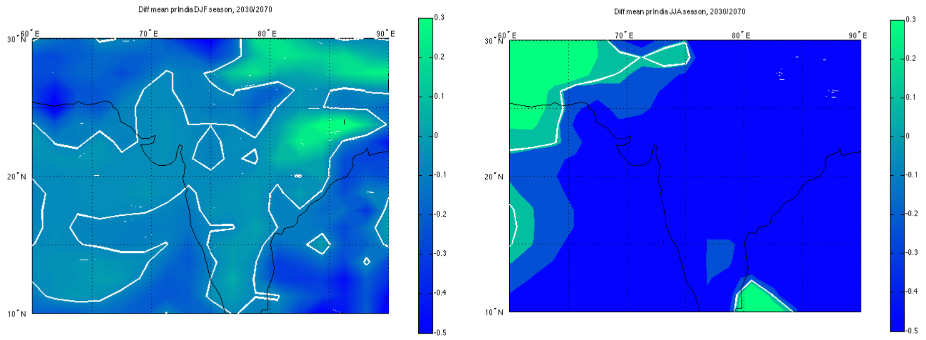


Figure 4.8: Mean pr differences in mm d^{-1} for India, period 2030/2070. 20a: DJF season; 20b: JJA season.

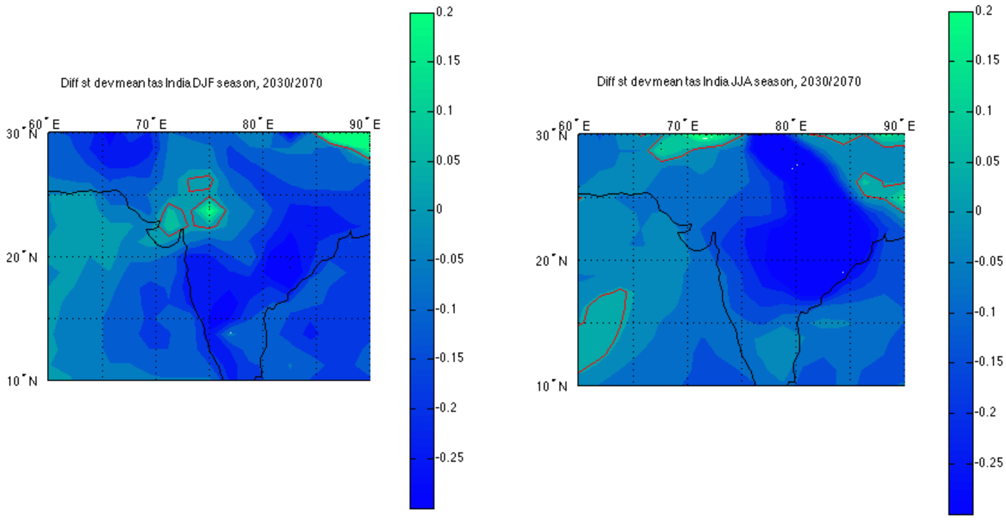


Figure 4.9: Standard deviation tas differences in K for India, period 2030/2070. 20a: DJF season; 20b: JJA season.

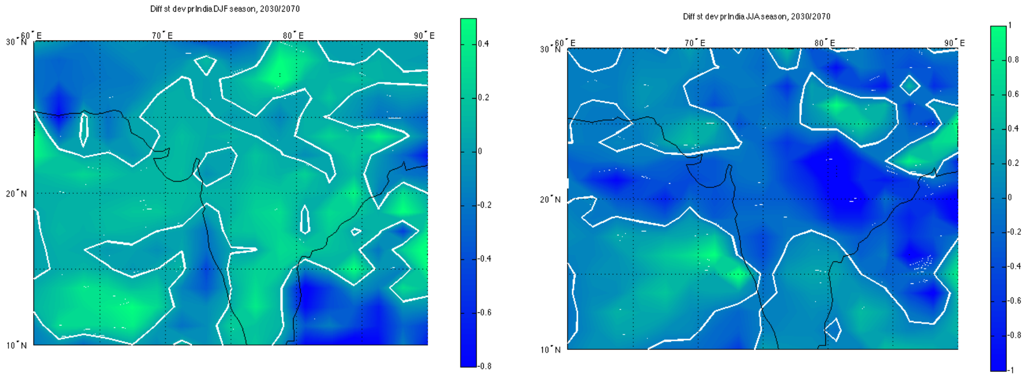


Figure 4.10: Standard deviation pr differences in mm d^{-1} for India, period 2030/2070. 20a: DJF season; 20b: JJA season.

total precipitation, Figg.(4.12), linear trends of the geoengineered and reference models for both DJF and JJA season, referring to the period 2030/2070. They are in complete agreement with what we have deduced by the maps projections.

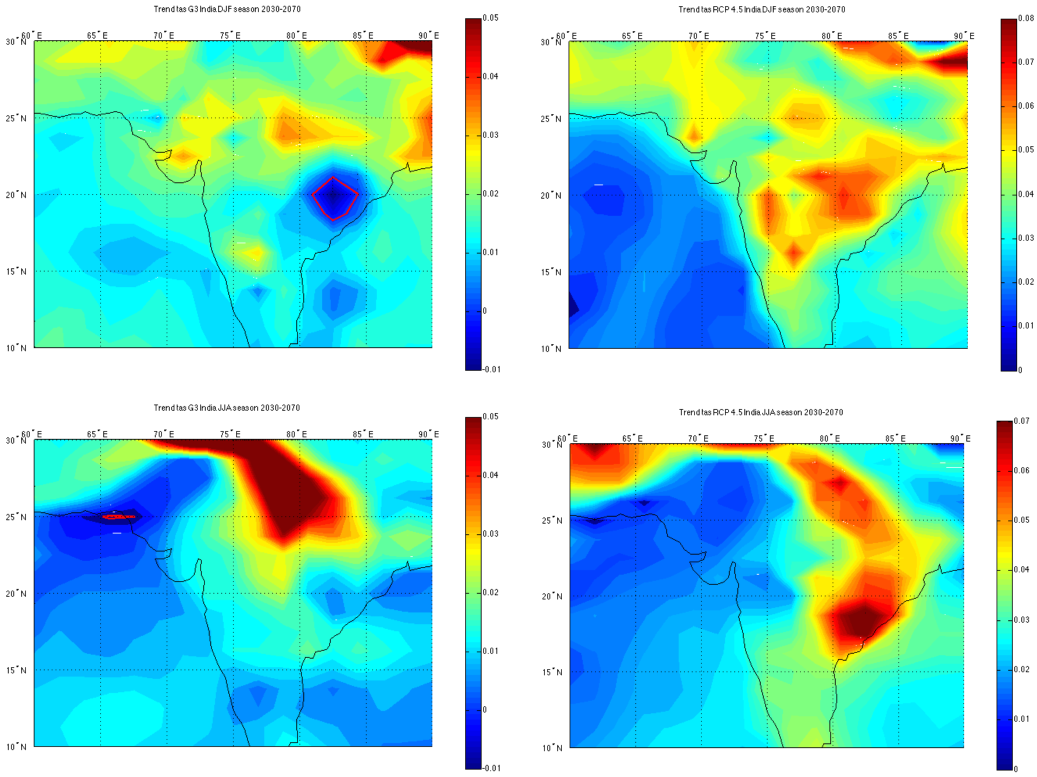


Figure 4.11: Trend tas India in K $y^{-1}$for DJF and JJA season, period 2030/2070. 23a,c: G3; 23b,d: RCP 4.5

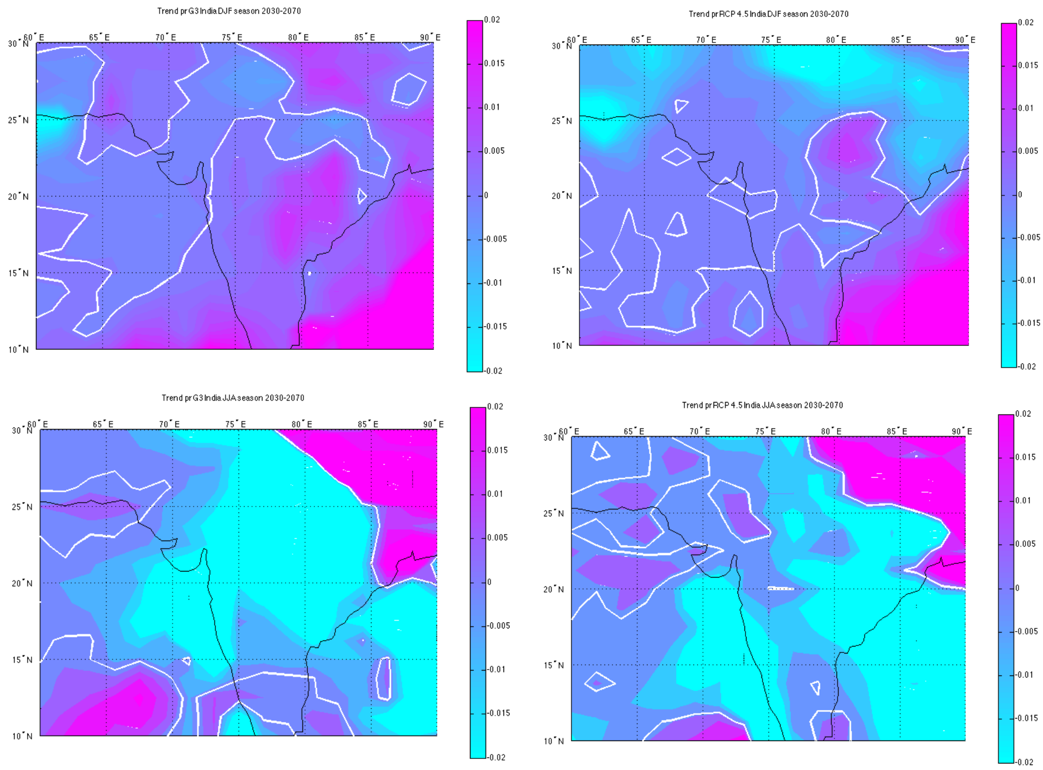


Figure 4.12: Trend pr India in mm d^{-1} y^{-1} for DJF and JJA season, period 2030/2070. 23a,c: G3; 23b,d: RCP 4.5

Chapter 5

Conclusions and Final Remarks

We sketch below the main conclusions of this thesis:

- We have performed a numerical study of geoengineered model G3 w.r.t. the reference scenario RCP 4.5, both on a global scale and on local summer Indian monsoon scale.
- On global scale, the alleviation of the global warming by a G3 scenario would be undoubtable. However, this global cooling turns out to be not uniform on the planet: that is, it would be quite remarkable on the Arctic, thus alleviating the Arctic amplification phenomenon, while quite absent on the equatorial strip.
- The G3 cooling projection has shown to be more effective on land than on the sea (in agreement to the well-known different heat capacity of land and ocean).
- The cooling by a type-G3 geoengineering method would be stronger in North Hemisphere winter (December-January-February, DJF) than in NH summer (June-July-August, JJA).
- Stratospheric geoengineering so as to compensate for increased greenhouse gases concentrations, thus reducing the global temperature increase (which, by the way, would always be there, as one does not intervene on the reduction of GHGs concentrations but only compensate their effects by the reduction of the Earth's albedo), would cause a reduction in the summer Indian yearly mean monsoon rainfall (while we have an increase in the winter monsoon);
- The conclusions of our preliminary study concerning rainfalls are more tricky and complicated, also given the intimate complexity of the variable itself. By the way, we can fairly state that, even if annual average G3 changes in precipitation turn out to be very small in percentage, our projections show: decrease of

rainfall in the ITC zone, North Pacific, northern Indian Ocean and North-West Atlantic Ocean, South Atlantic, equatorial Africa and on India, Russia and all Europe, except from almost all Italy. Net but slight decrement also over the equatorial strip. On the other side, there would be an increase of showers in the South Pacific, South Indian Ocean and the North-East Atlantic Ocean, Australia, North-Africa (less markedly also on the extreme south), and coastal Antarctica.

- As for the winter and summer Indian monsoon, our simulations predict an anomalous increase in rainfalls on the southern Arabian sea and, on-land, on the North-East and central India (as well as on Sri-Lanka) in DJF and a decrease elsewhere. Here, the word 'anomalous' means the G3 scenario does not reflect for precipitation the general decrease in temperatures as well as the typical dryness of the winter Indian monsoon. This anomalous increase is even more marked in season JJA if we consider again the Northern-India; while there is a sensible decrease of rainfalls over the central East and coastal South.

We would also like to remark that, although our numerical study is surely a preliminary one, primarily because it is affected by some errors, it turns out to be pioneering for it lets us understand the validity of some of the perplexities concerning the deployment of geoengineering techniques into the atmosphere. In particular, given the turmoil caused on the summer Indian monsoon, and given the fact that the local deployment of sulphates would obviously not remain confined, if a single nation one day autonomously decided to take advantage by a geoengineering technique, this would affect the global climate with uncertain consequences.

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