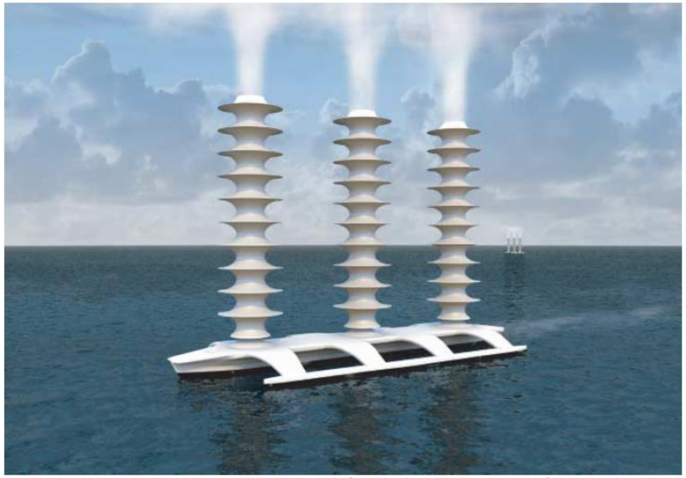
Salter et al. (2008: PTRSA)

Preliminary analysis of the multi-model **GeoMIP G4cdnc** exercise

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Jón Egill Kristjánsson, UiO
Helene Muri, UiO
+ contributing modeling groups

GeoMIP MCB design and objectives

Table 1. A Summary of the Three Sea Spray Geoengineering Experiments in This Paper[a]

Experiment	Description
G1ocean-albedo	Instantaneously quadruple the preindustrial CO_2 concentration while simultaneously increasing ocean albedo to counteract this forcing.
G4cdnc	In combination with RCP4.5 forcing, starting in 2021, increase cloud droplet number concentration by 50% over the ocean.
G4sea-salt	In combination with RCP4.5 forcing, starting in 2021, increase sea spray emissions in the marine boundary layer between 30°S and 30°N by a uniform amount, with an additional total flux of sea spray aerosols that results in a global-mean ERF of $-2.0\,\mathrm{W\,m^{-2}}$.

[a]Schematics of these experiments can be found in Figure 2. Each simulation is to be run for 50 years with sea spray geoengineering, followed by 20 years in which geoengineering is ceased. A 10 year fixed sea surface temperature experiment is also requested to diagnose ERF.

Kravitz et al. (2013: JGR)

- *G1ocean-albedo*: General aspects of cooling over the oceans
- *G4cdnc*: No dependency on microphysics, but dependency on model cloud fields
- *G4sea-salt*: Allowing the models to calculate CDNC change explicitly from injected sea salt

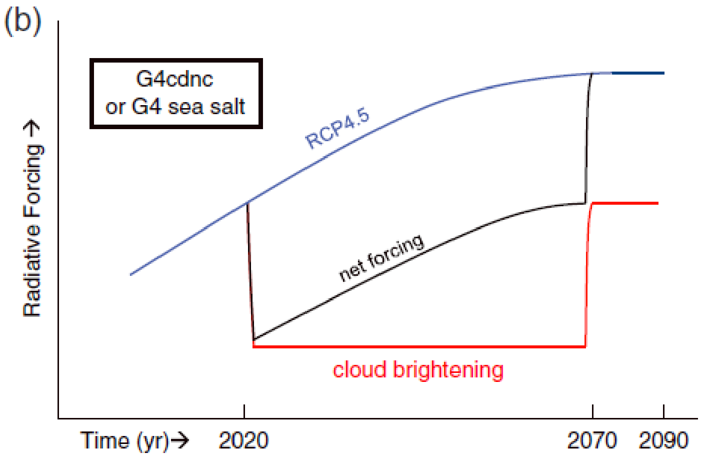
G4cdnc experiment, GeoMIP

- *All liquid cloud droplets over ocean regions at altitudes below 680 hPa (i.e.: the liquid droplets in warm clouds and in mixed-phase clouds) are identified.*
- *In these clouds,* ***cloud droplet number concentration (CDNC) is increased uniformly by 50 %.***

- G4cdnc experiments are run for 2020-2070, followed by termination
- Below, G4cdnc-RCP4.5 differences are calculated based on years 2035-2065

Data available from 9 models:

- HadGEM2
- CanESM2
- CSIRO-Mk3L-1
- IPSL-CM5A-LR
- MIROC-ESM
- MPI-ESM-LR
- BNU-ESM
- GISS-E2-R
- NorESM-1



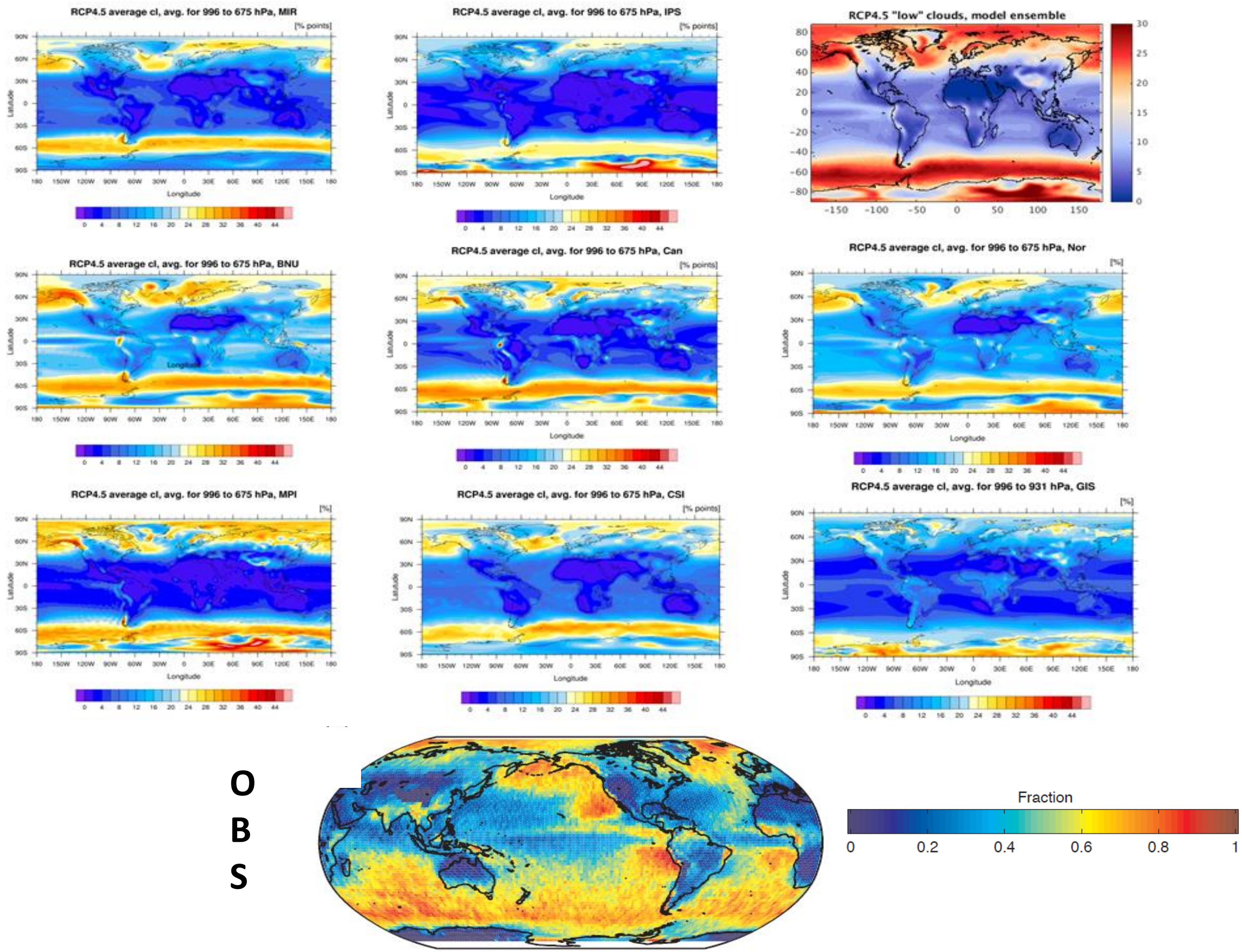
Kravitz et al. (2013: JGR)

Participating Models

Model	No. of gridcells (lat x lon)	No. of vert layers (type)	RCP4.5 / G4cdnc realizations	Representation of aerosol indirect effect	Contact person
BNU-ESM	64 x 128	26 (hybrid sigma)	1 / 1	Single-moment microphysics scheme; Rasch and Kristjansson (1998) with modification by Zhang et al. (2003). NOTE: To achieve effects of 50% increase of CDNC over ocean regions below 680 hPa, a direct alteration of liquid droplet size by dividing (1.5^(1/3)) is done.	Duoying Ji duoyingji@gmail.com
CanESM2	64 x 128	35 (hybrid sigma)	5 / 3	Prognostic microphysics scheme accounting for the first indirect effect but not the second indirect effect (von Salzen et al., 2013)	Jason N. Cole Jason.Cole@ec.gc.ca
CSIRO-Mk3L-1-2	56 x 64	18 (hybrid sigma)	3 / 3	Prescribed CDNC	Steven Phipps s.phipps@unsw.edu.au
GISS-E2-R	90 x 144	29 (hybrid sigma)	3 / 3	Prognostic calculations of CDNC (Menon et al., 2010), based on Morrison and Gettelman (2008).	Ben Kravitz ben.kravitz@pnnl.gov
HadGEM2-ES	145 x 192	38 (hybrid height)	4 / 1	Diagnostic CDNC scheme based on Jones et al. (2001)	Andy Jones andy.jones@metoffice.gov.uk
IPSL-CM5A-LR	96 x 96	39 (hybrid sigma)	4 / 1	Cloud droplet number concentration is computed from the total mass of soluble aerosol through the prognostic equation from Boucher and Lohmann (1995)	Olivier Boucher olivier.boucher@lmd.jussieu.fr
MIROC-ESM	64 x 128	80 (hybrid sigma)	1 / 1	Prognostic calculation of CDNC (Abdul-Razzak and Ghan, 2000))	Shingo Watanabe wnabe@jamstec.go.jp
MPI-ESM-LR	96 x 192	47 (hybrid sigma)	1 / 1	Prescribed CDNC	Ulrike Niemeier ulrike.niemeier@zmaw.de
NorESM1-M	96 x 144	26 (hybrid sigma)	1 / 1	Prognostic calculation of CDNC (Hoose et al., 2009; Abdul-Razzak and Ghan, 2000; Morrison and Gettelman, 2008)	Helene Muri helene.muri@geo.uio.no

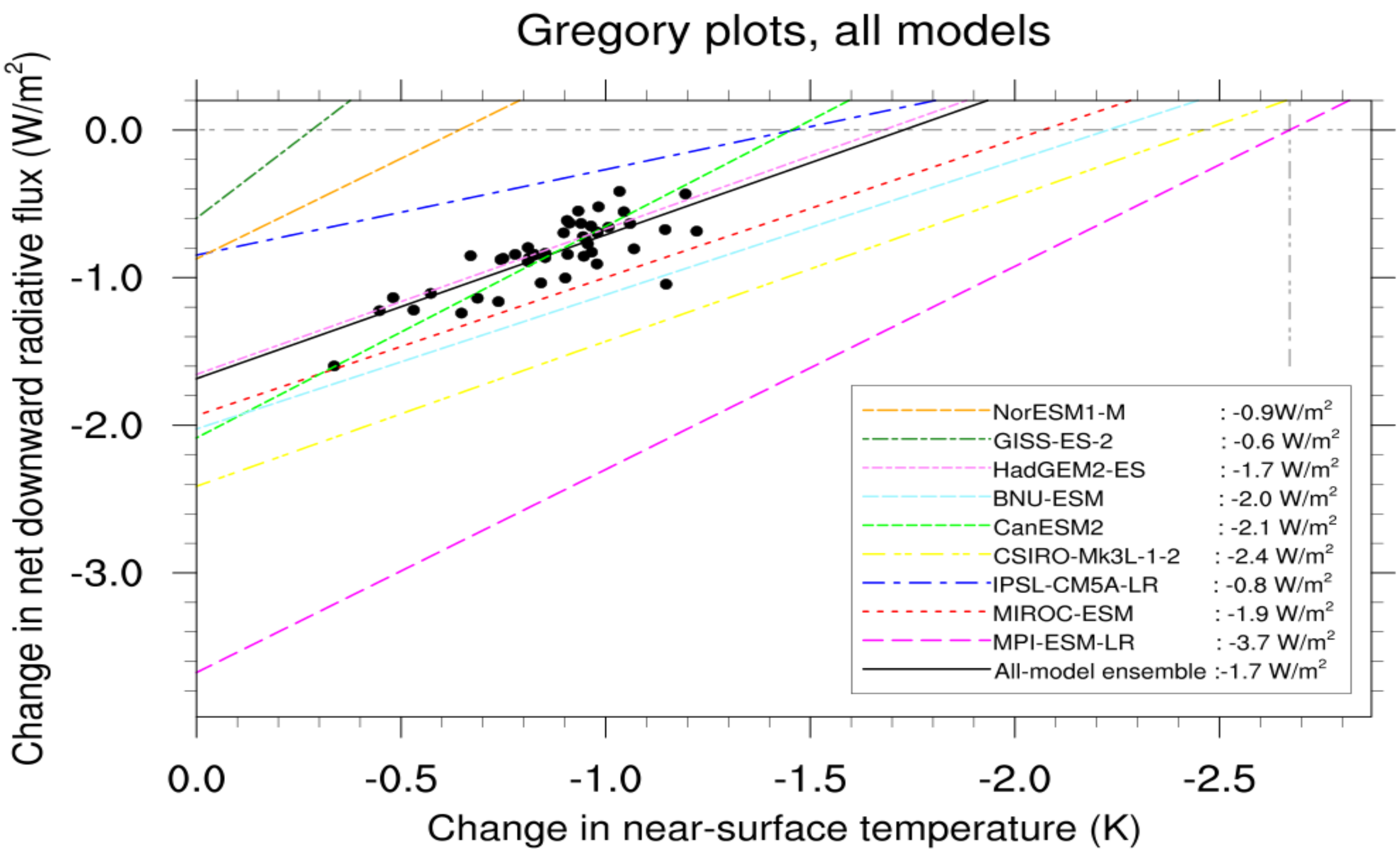
Location of «low clouds», 8 of 9 models

«Low clouds»: **vertical average** of cloud cover (variable cl) in all layers below 675 hPa, average of years 2035-2065 of the RCP4.5 experiment

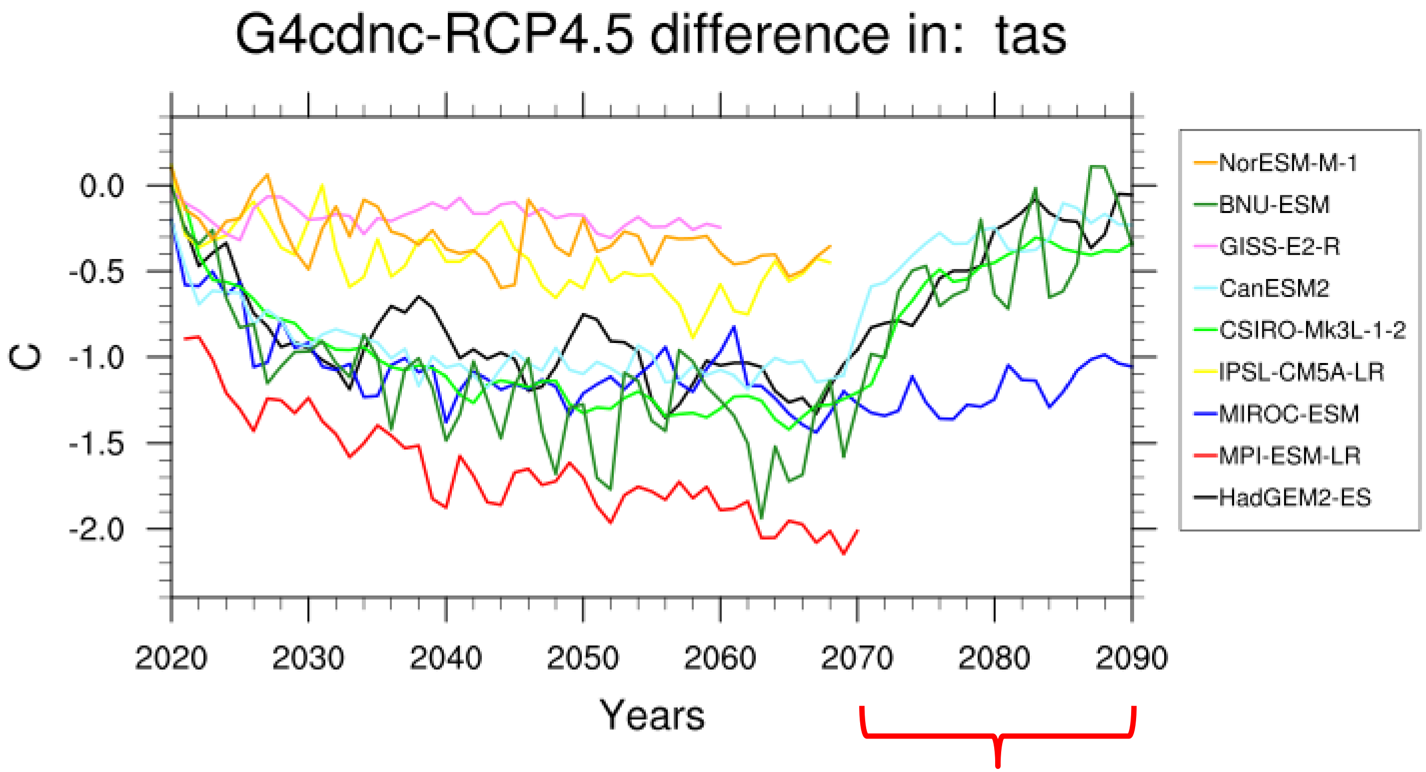


Radiative forcing for RCP4.5-G4cdnc: $-1.7\ W\ m^{-2}$

Years 2035-2065 of the experiment are used in the calculation

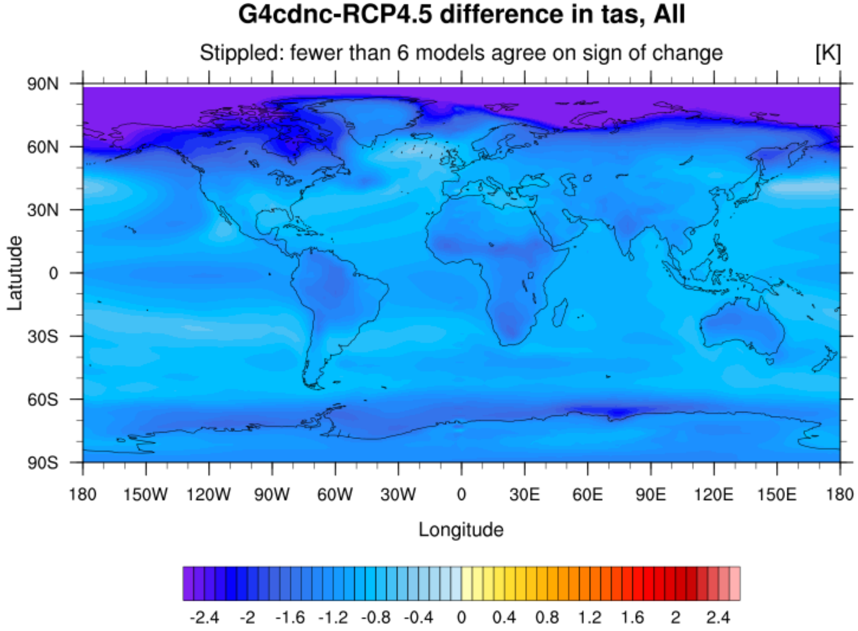


Surface Temperature evolution



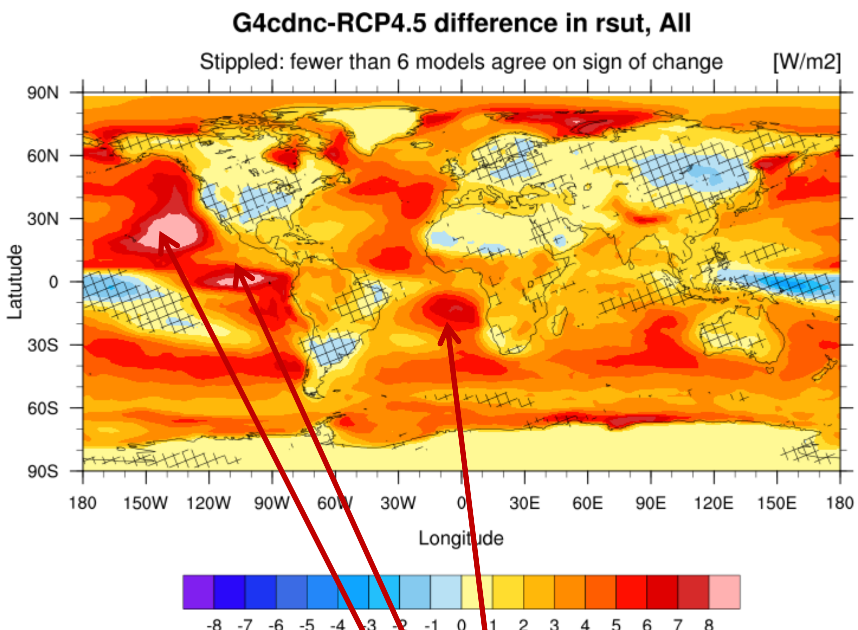
Termination Effect

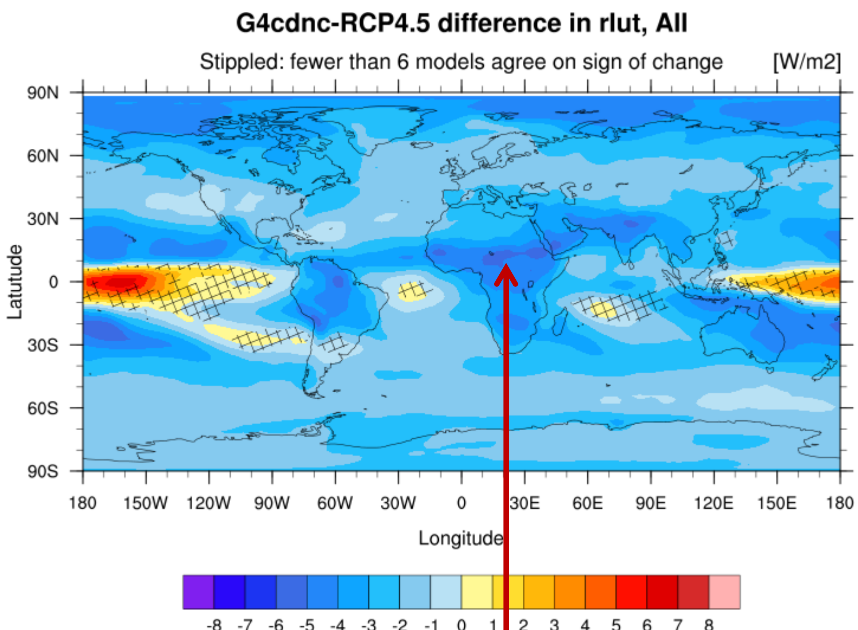
Temperature Change



- Arctic amplification of the cooling signal
- Stronger cooling in regions of low clouds?
- Global cooling: -1.0°C
- <u>Low-latitudes</u>: more cooling over land than over oceans

TOA SW change TOA LW change

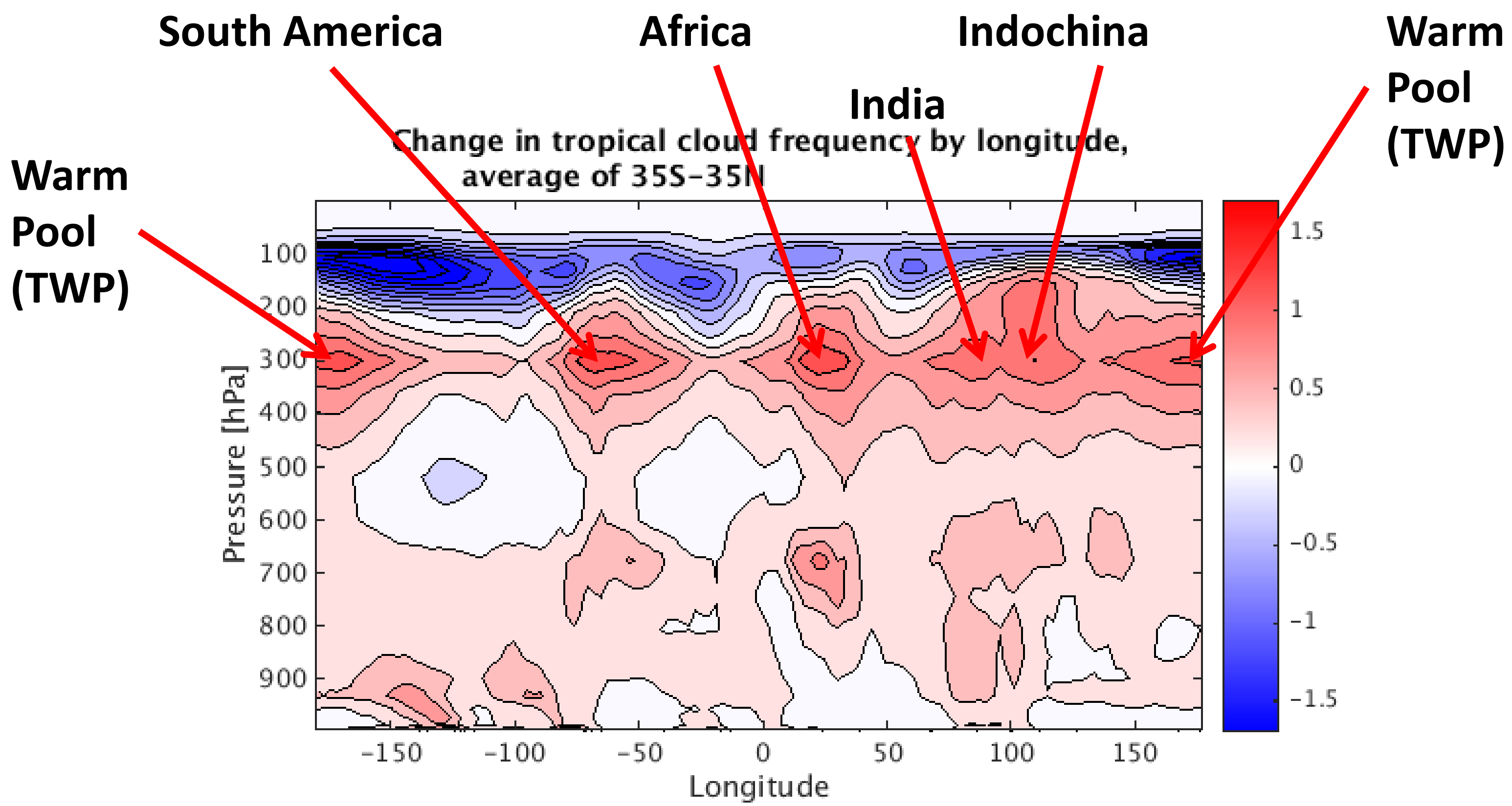




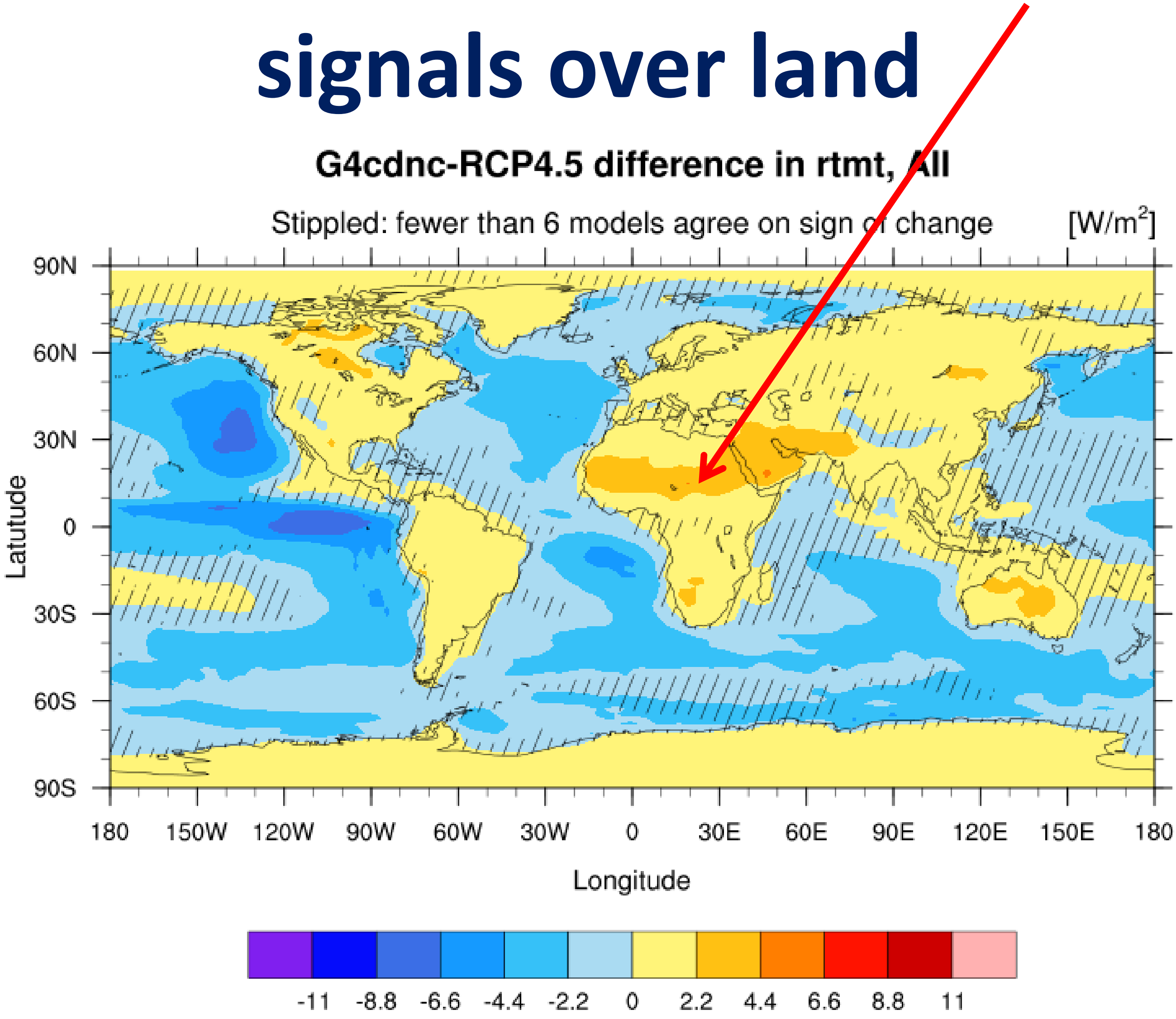
Strong albedo response in regions of low-latitude low clouds with clear air above

- Negative values due to colder climate
- Large negative values in regions of enhanced convection

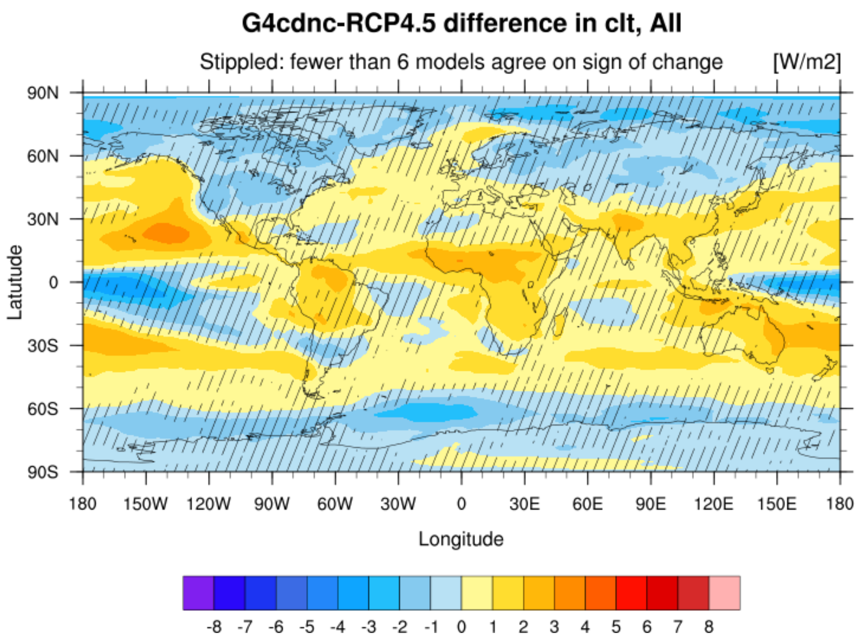
Low-latitude cloud changes



Net TOA Flux change: **Compensating signals over land**

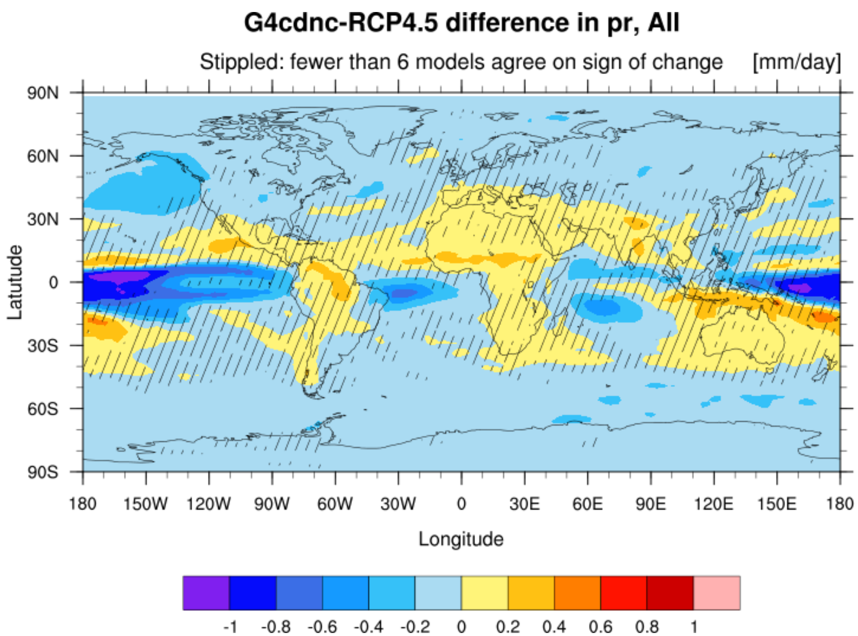


Total Cloud Cover change



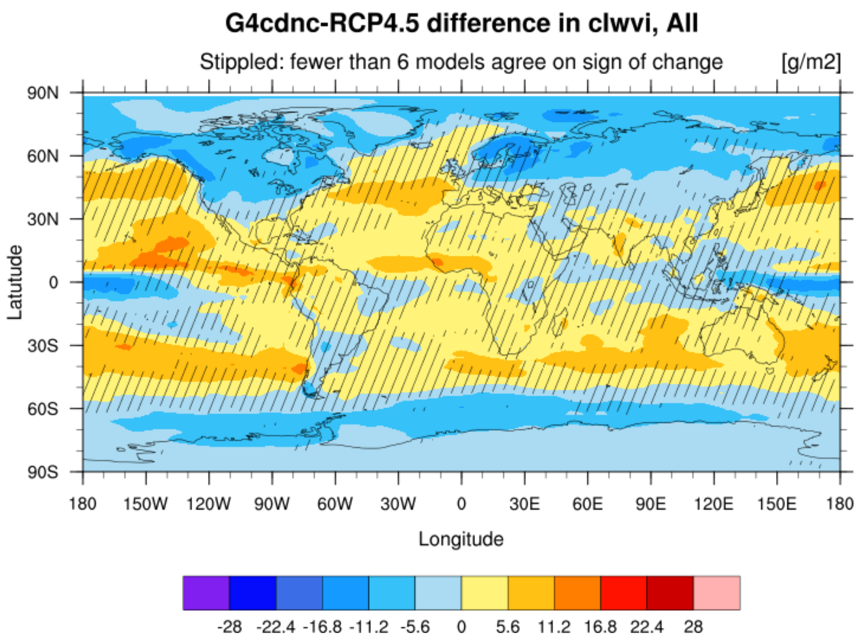
- Global multi-model mean change: +0.39 %-points
- **Higher cloud cover certain ocean regions**
- **Higher cloud cover over low-lat land regions**
- Poles: decreasing cloud cover

Precipitation change



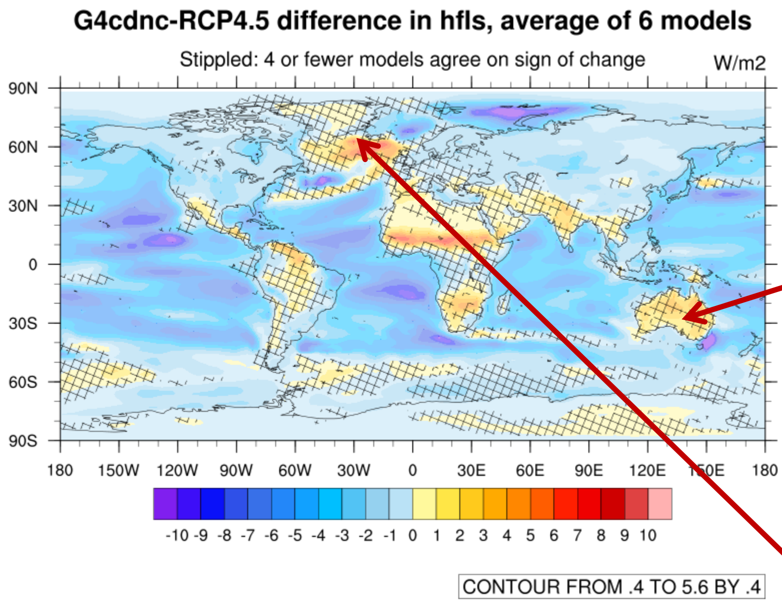
- Global: - 0.076 mm/day change in precipitation, partly because the G4cdnc climate is cooler than RCP4.5
- Low-latitudes: 0.03 mm/day **increase over land**, 0.08 mm/day decrease over oceans
- Particularly strong reduction around the Pacific ITCZ

Liquid Water Path change



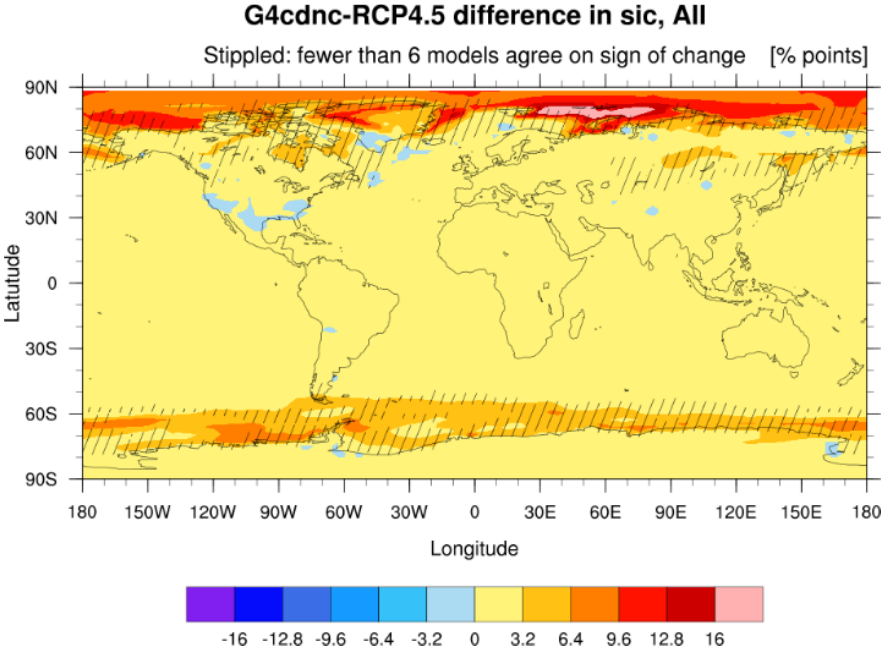
- **Increases over ocean regions with denser clouds (Lifetime Effect?)**
- **Increase over many low-lat land regions**
- Decrease at mid-to high-lat due to colder climate

Latent Heat Flux change



- General reduction over ocean due to colder climate
- LH flux increases over North Africa, northern India, the Amazon, and Australia
- All models agree on the strong increase in LH flux south of Iceland. Cause??

Sea Ice Change



Globally averaged changes

	Forcing	Cloud cover	Temperature	Precipitation	Condensed water path	Low clouds
BNU-ESM	-2.0	-0.30 **	-1.32 **	-0.10 **	-1.0**	0.33**
CanESM2	-2.1	0.16 **	-1.06 **	-0.07 *	-2.1**	0.15**
CSIRO-Mk3L-1-2	-2.4	0.77 **	-1.22 **	-0.09 **	3.1**	0.52**
GISS-E2-R	-0.6	0.05	-0.18 **	-0.02 **	-1.1**	---
HadGEM2-ES	-1.7	0.52 **	-0.99 **	-0.07 **	---	---
IPSL-CM5A-LR	-0.8	0.60 **	-0.52 **	-0.05 **	-1.5 **	0.16**
MIROC-ESM	-1.9	0.14 **	-1.13 **	-0.08 **	-6.6**	-0.12**
MPI-ESM-LR	-3.7	1.16 **	-1.76 **	-0.14 **	4.0**	0.61**
NorESM1-M	-0.9	-0.07 **	-0.35 **	-0.02 **	-1.1**	-0.05**
Inter-model average						

Table 3: As Table 2, but for the *G4cdnc* minus *RCP4.5* difference in the same variables, and including the total radiative forcing. One asterix denotes 95 % significance by the Kruskal-Wallis test, while two denote 99% significance.

Low-latitude circulation changes

- The table below shows G4cdnc-RCP4.5 changes at low-latitudes (defined as the latitude band from 35°S to 35°N), for all grid cells and for land and ocean grid cells separately.

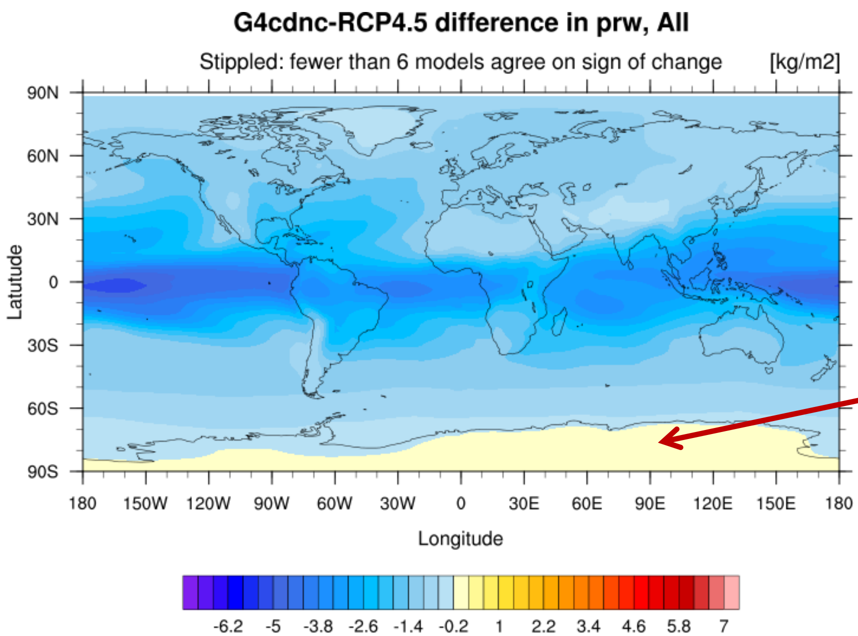
	Total	Land	Ocean
Net downward flux, TOA (rtmt)	-0.52	1.26	-0.17
Outgoing LW radiation (rlut)	-2.56	-4.77	-1.76
Outgoing SW radiation (rsut)	2.16	1.21	2.5
Outgoing LW radiation, clear sky (rlutcs)	-1.06	-1.8	-0.79
Outgoing SW radiation, clearsky (rsutcs)	0.24	-0.15	0.38
Water vapor path (prw)	-1.64	-1.07	-1.85
Liquid water path (clwvi)	1.28	0.93	1.4
Surface upward latent heat flux (hfls)	-2.13	0.21	-2.99
Surface upward sensible heat flux (hfss)	-0.01	-0.77	0.27
Total cloud cover (clt)	0.59	0.86	0.49
Precipitation (pr)	-0.05	0.03	-0.08
Near-surface air temperature (tas)	-0.7	-0.9	-0.7

Table x: Changes due to climate engineering (G4cdnc-RCP4.5) averaged over all models, for low latitudes (35°S-35°N) only.

Preliminary Findings

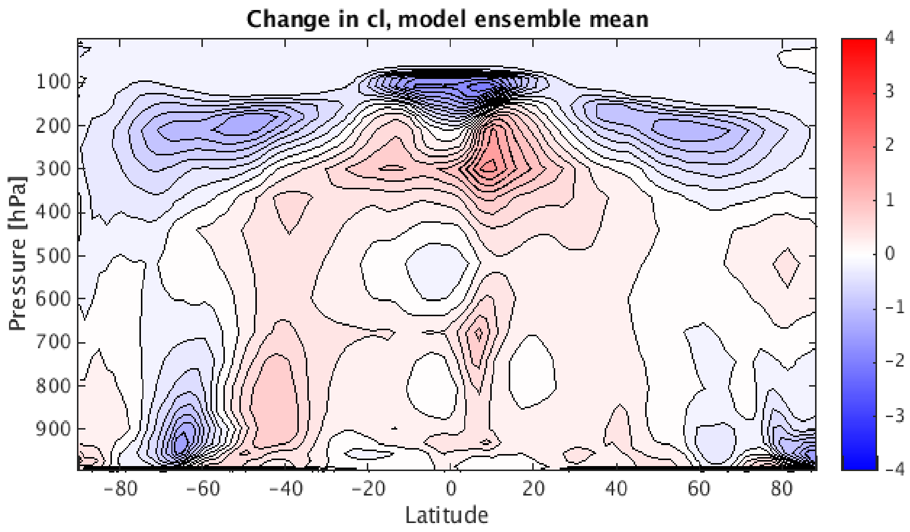
- **So far, 9 models have run the experiment**: 3 of them obtain a very weak cooling (0.5 K or less), 5 of them obtain about 1 K cooling and 1 of them about 2 K cooling
- Average radiative forcing: -1.8 W m^{-2}
- Average global temperature change: -1.0 K
- **“Enhanced Walker Circulation effect”:** Strong negative TOA SW forcing over subtropical oceans; compensating rising motion and positive TOA LW signal over adjacent land regions

Water Vapor Path change



- Decreases over most regions due to a colder climate in G4cdnc compared to RCP4.5
- Slight increase over Antarctica – Why?

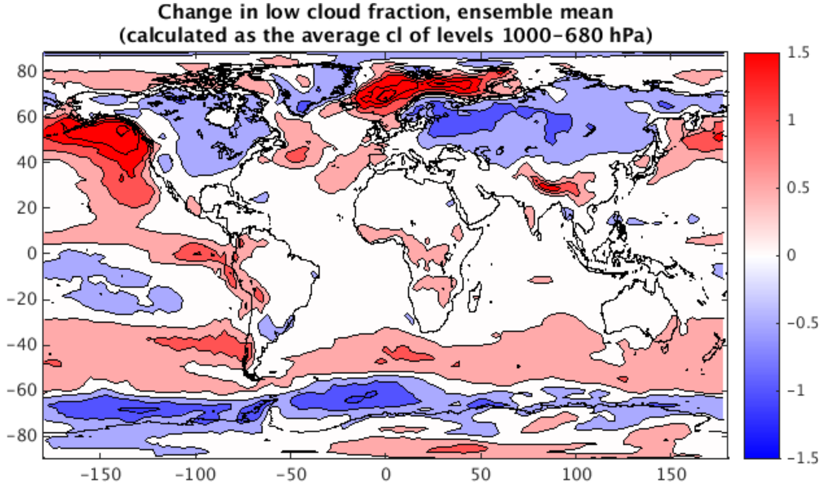
Cloud Cover change



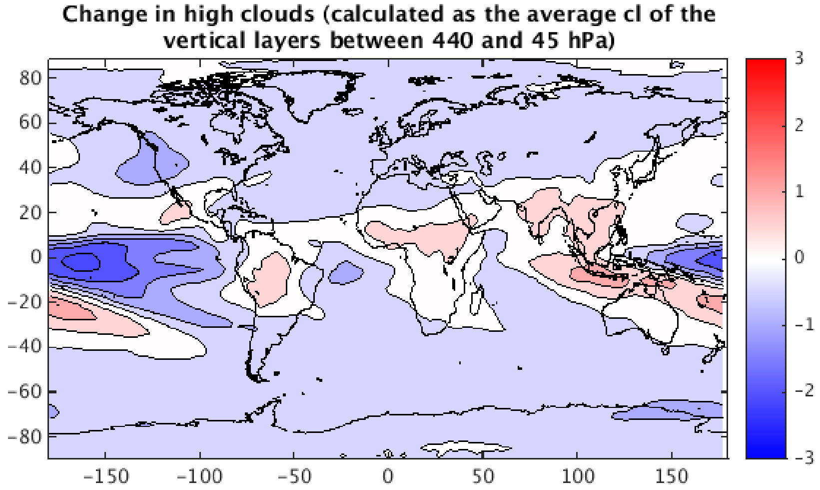
- Dominated by climate responses:
- Lower tropopause height
- Equatorward shift of storm tracks

Cloud Fraction change

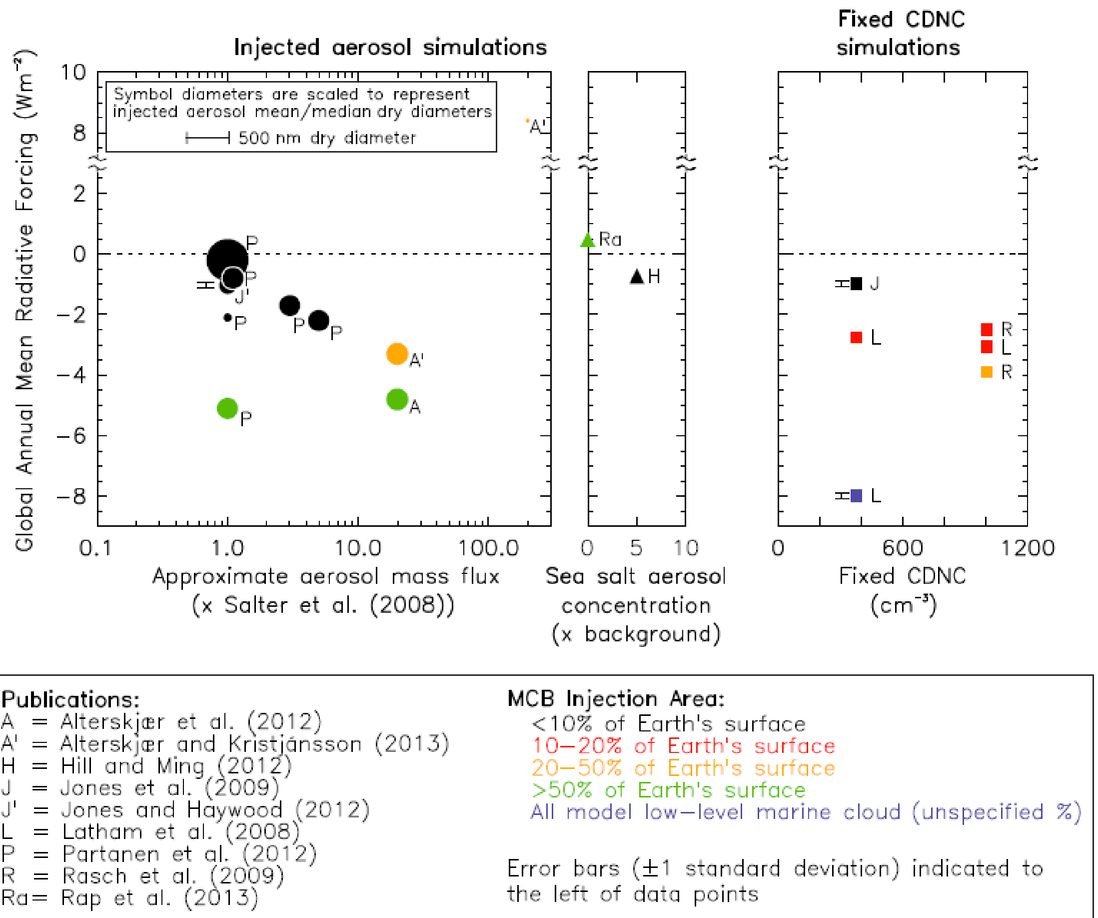
Low Clouds



High Clouds



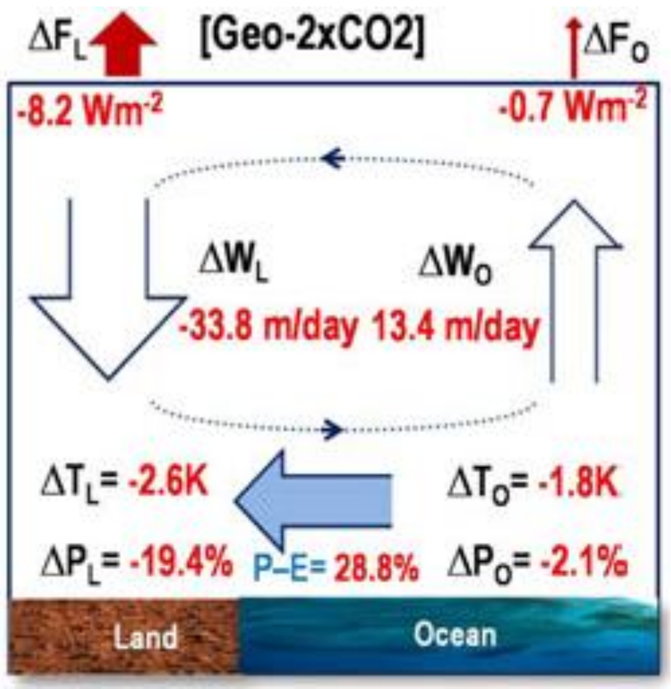
Need for a **co-ordinated, multi-model** approach



Kravitz et al. (2013: JGR)

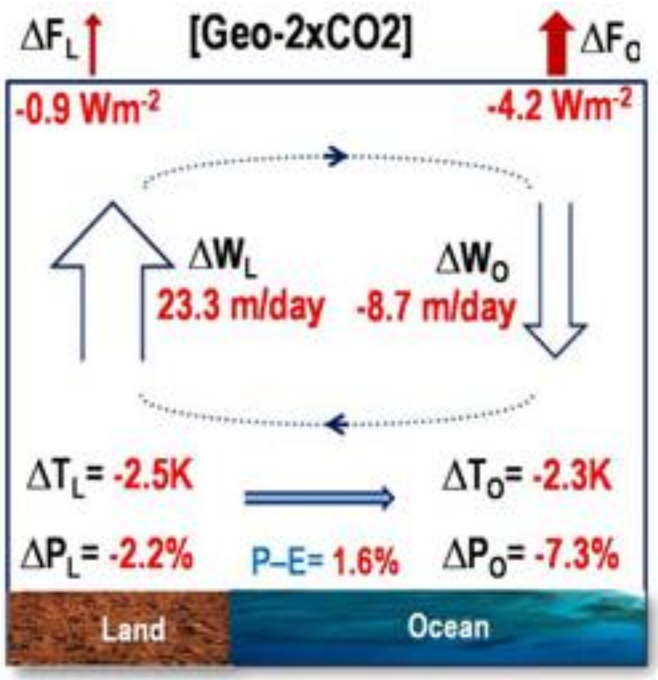
Land vs. Marine SRM

Land Cloud Brightening



Drier low-latitude land areas

Marine Cloud Brightening



Moister low-latitude land areas

Bala & Nag (2011; Clim.Dyn.)