Is the indirect forcing by aircraft soot positive or negative?

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Object of this study

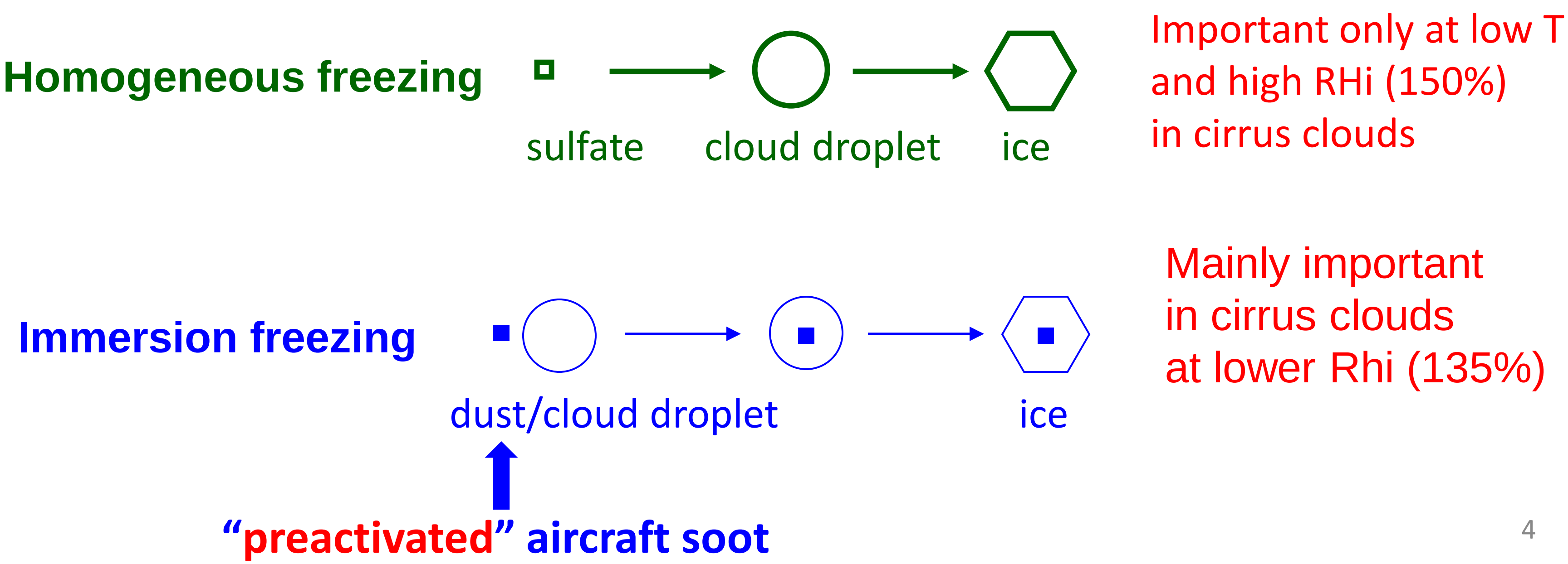
- Effect of aircraft soot as heterogeneous Ice Nuclei (IN) on large scale cirrus clouds (**NOT** linear contrail or contrail cirrus):
  - Radiative forcing
  - Hydrologic cycles

Methodology

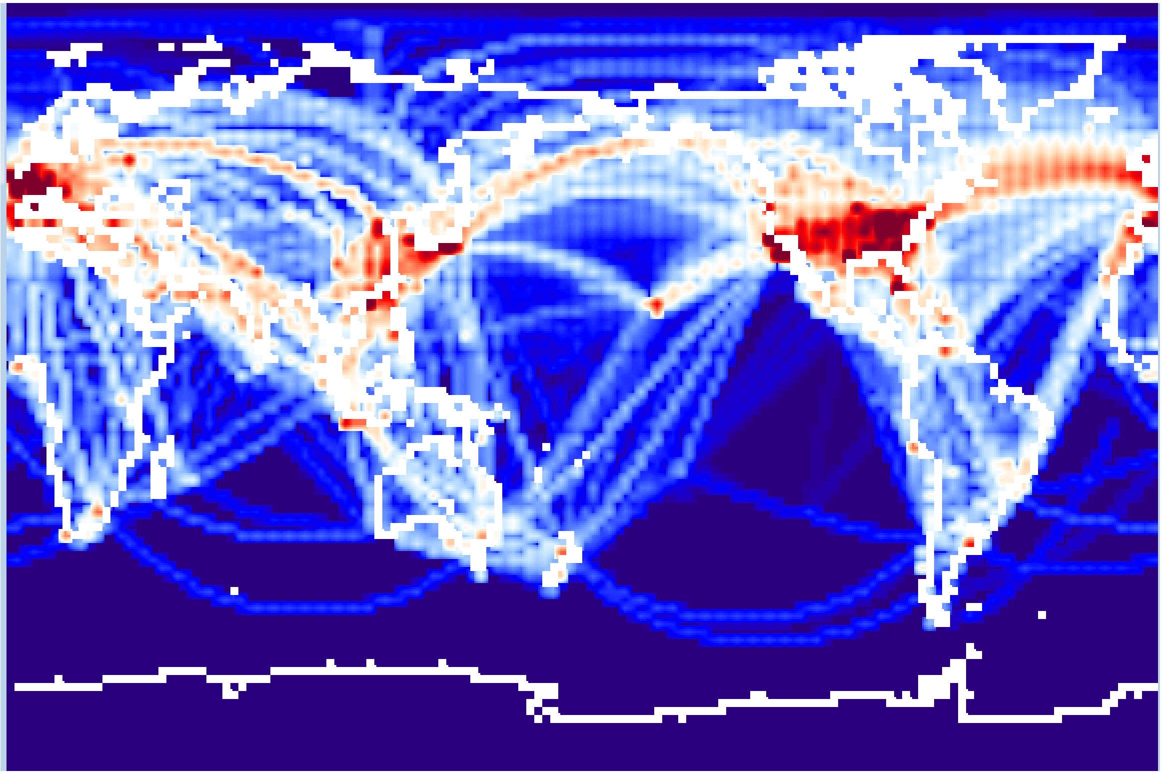
- We used a coupled CAM5/IMPACT model. The IMPACT module simulates a total of 17 aerosol types and/or size bins:
  - 3 sizes representing the number and mass of pure sulfate aerosols (i.e. nucleation, Aitken and accumulation modes),
  - 3 types of fossil/bio-fuel soot that depend on its hygroscopicity or the amount of sulfate on the soot
  - 1 biomass soot mode
  - 4 dust sizes
  - 4 sea salt sizes
  - **2 aircraft soot modes (preactivated in contrails or not)**
- The preactivated aircraft soot is added as extra heterogeneous Ice Nuclei (IN) to the CAM5/MAM3 in the cirrus ice nucleation process.

Ice nucleation parameterization in cirrus clouds in CAM5

- The standard CAM5 set-up uses ice parameterizations by Liu and Penner [2005] and Liu et al. [2007].
- It features competition between **Homogeneous freezing on sulfate** & **heterogeneous nucleation (Immersion freezing on dust)**



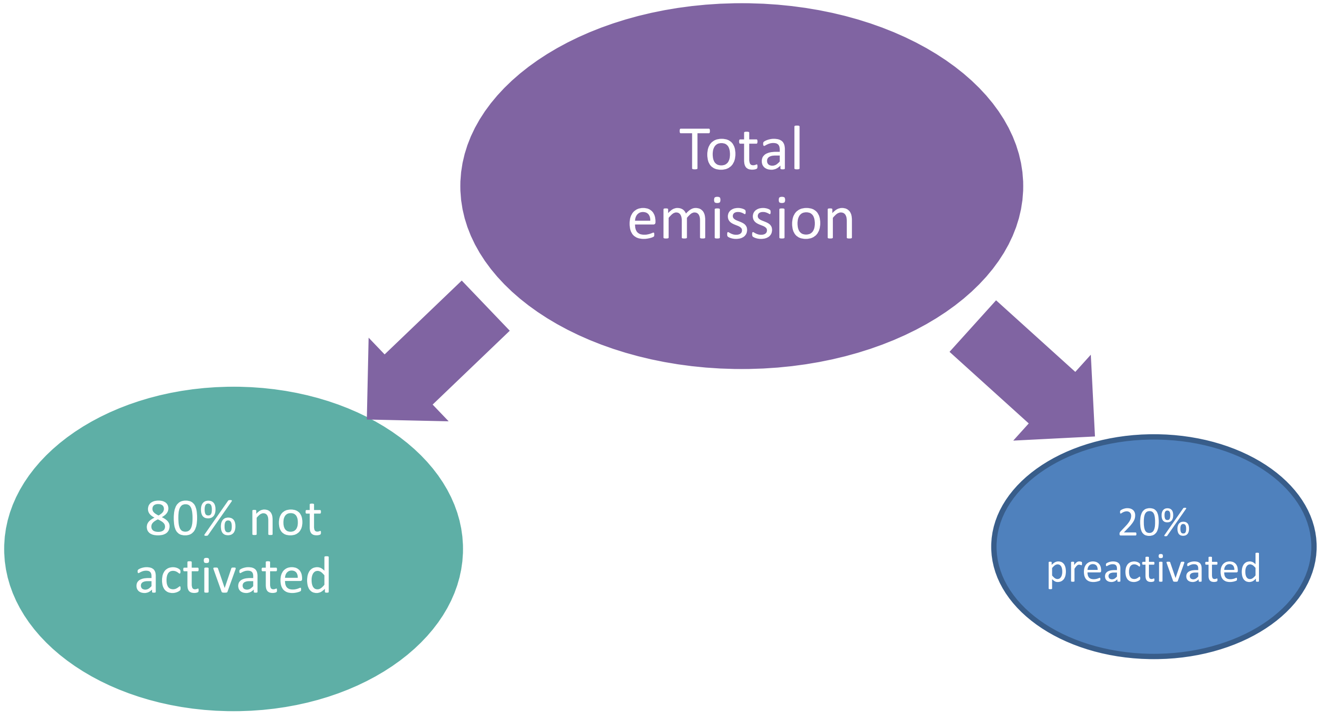
Aircraft soot emission



1. **Year 2006 emission from Aviation Environment Design Tool (AEDT).**
2. **We used hourly emissions of both BC and OM.**

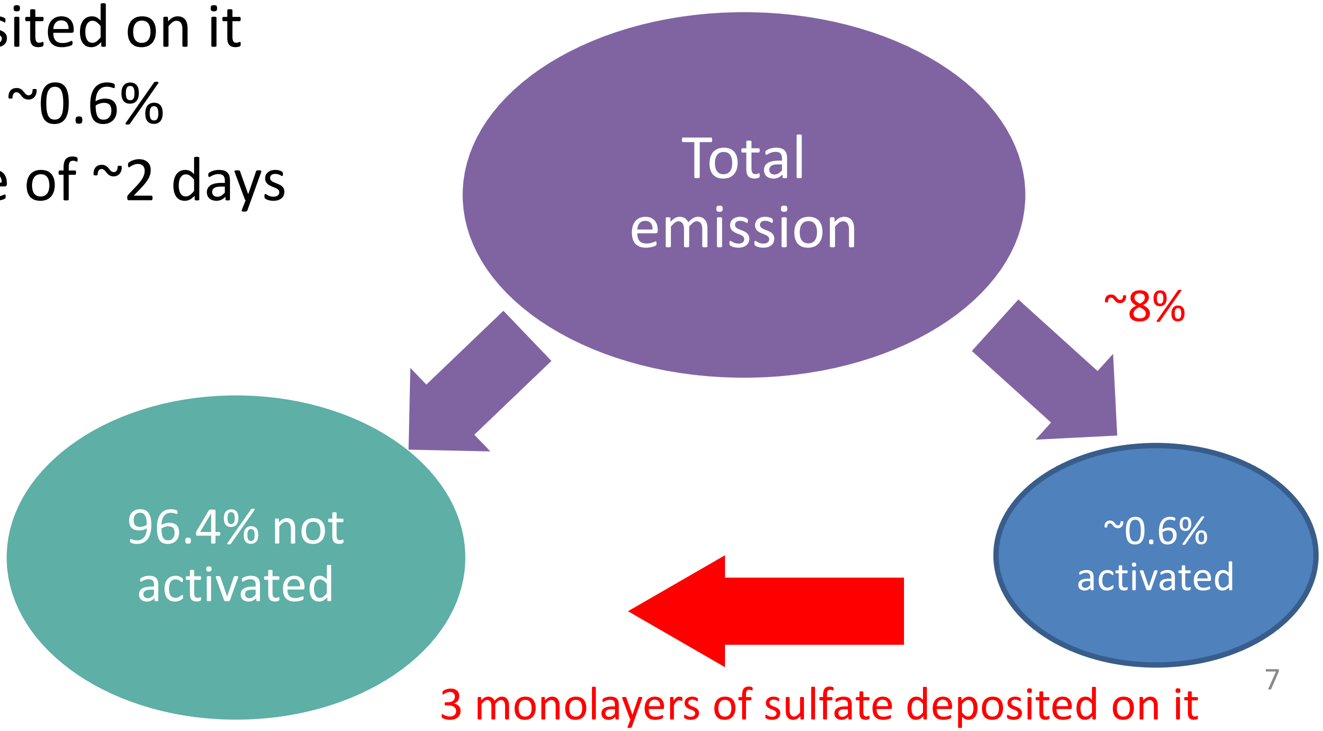
Aircraft soot acting as ice nuclei (IN) – 20%

- Based on the CoCiP model (Schumann, 2012)
- 20% is "preactivated" in contrails
- has a lifetime of ~30 days

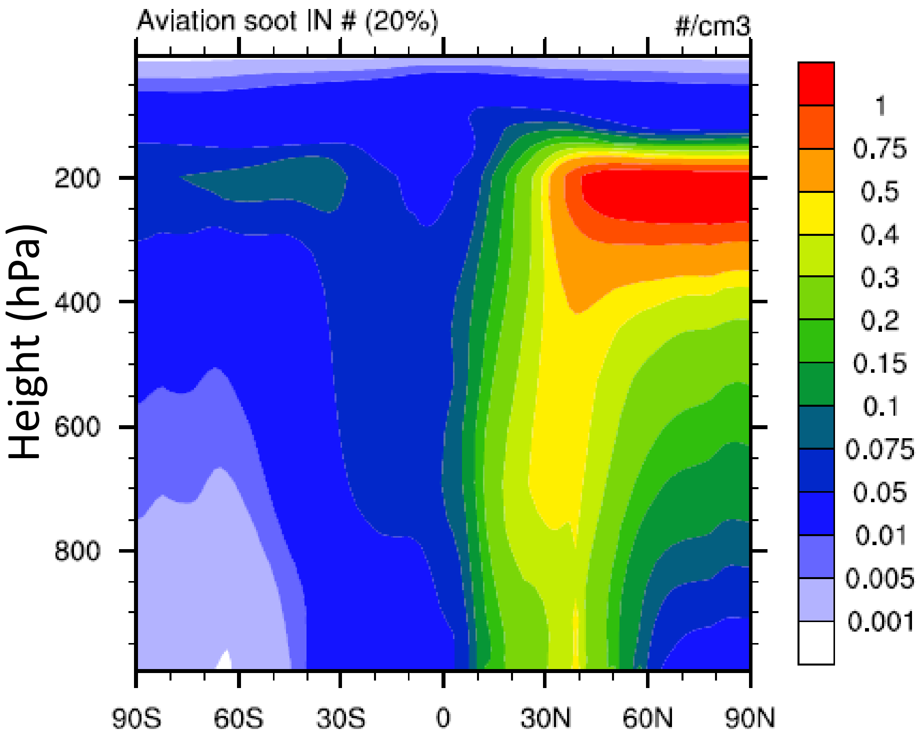


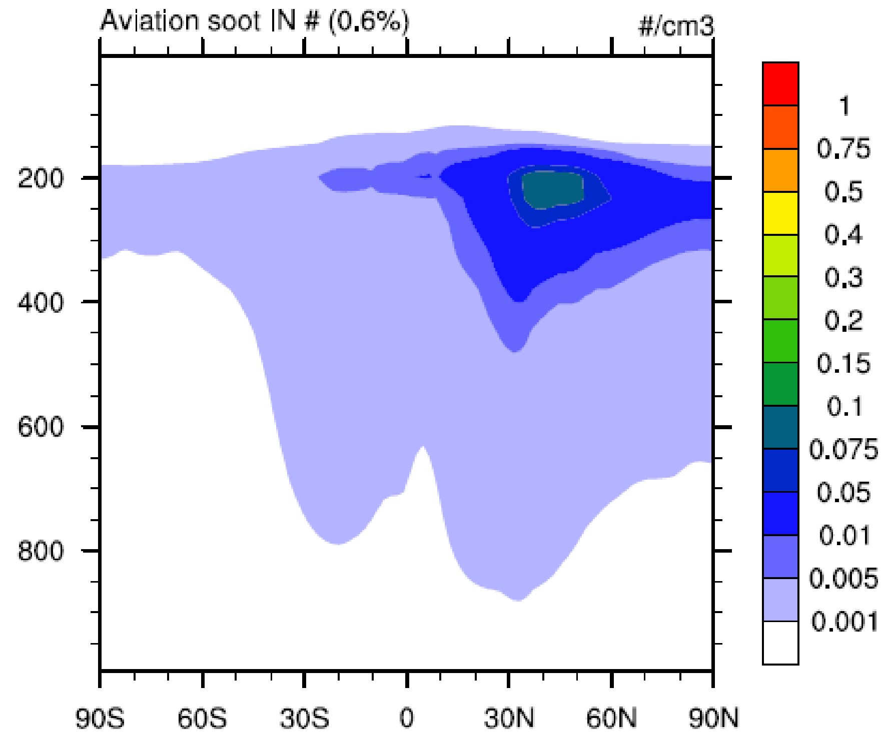
Aircraft soot acting as ice nuclei (IN) – ~0.6%

- Based on Schimdt-Appleman Criteria
  - ambient T < Tcritical
  - ambient RH < RHcritical
  - RHi > 1 (persistent contrail cirrus)
- ~8% forms persistent contrail cirrus
- lose its capability to act as an IN if more than 3 monolayers of sulfate deposited on it
- final fraction ~0.6%
- has a lifetime of ~2 days



Zonal mean “preactivated” aircraft soot number

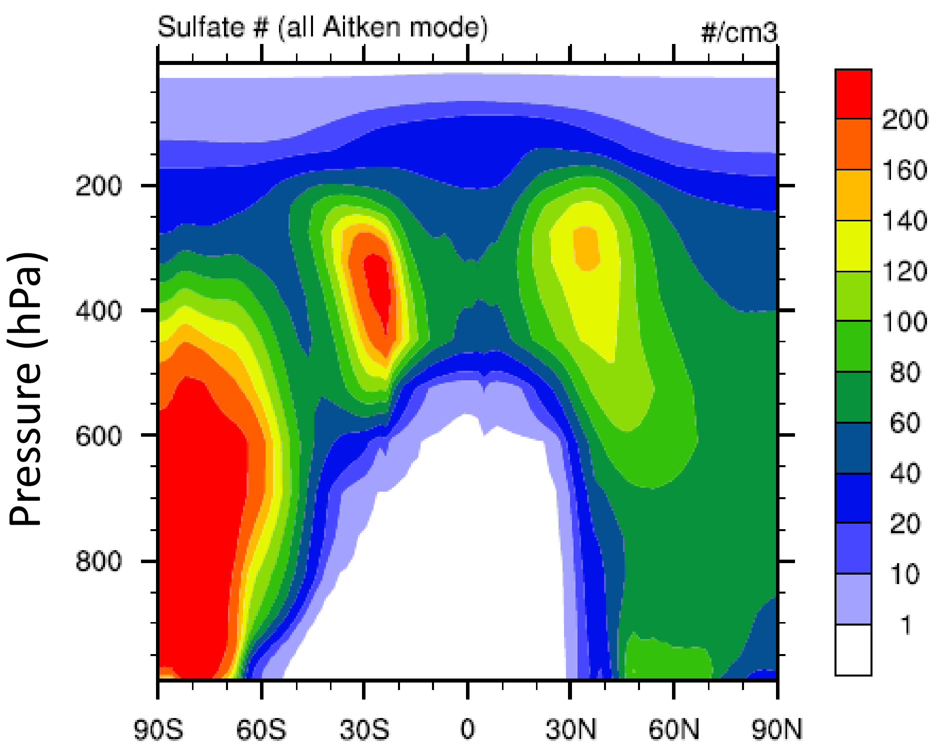




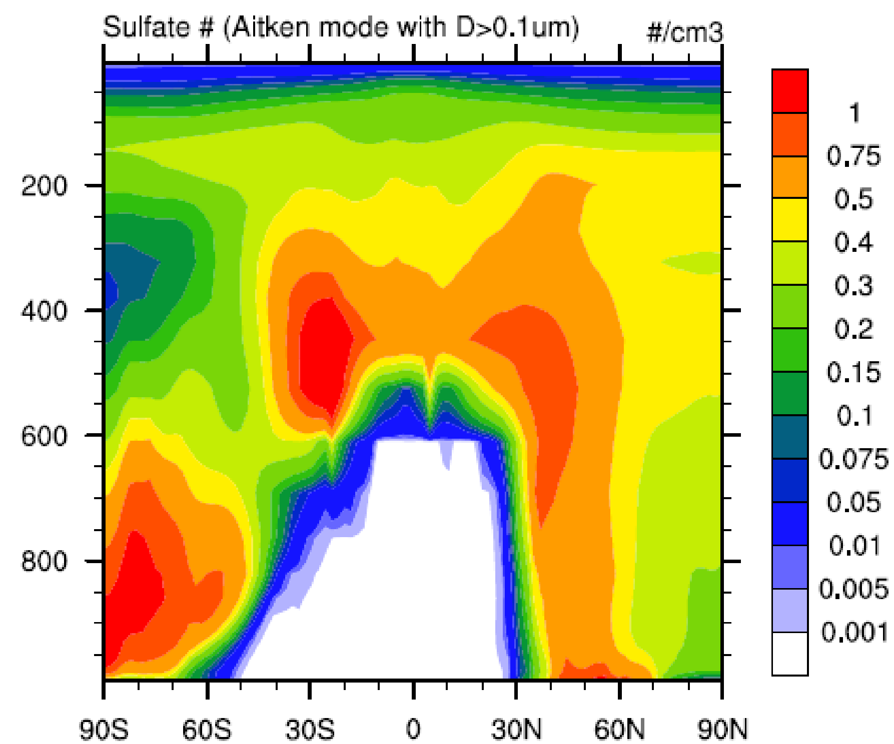
- **20% case**
- **~30-day lifetime**
- **comparable to total dust number**

- **~0.6% case**
- **~2-day lifetime**

Background sulfate/dust numbers used in LP scheme



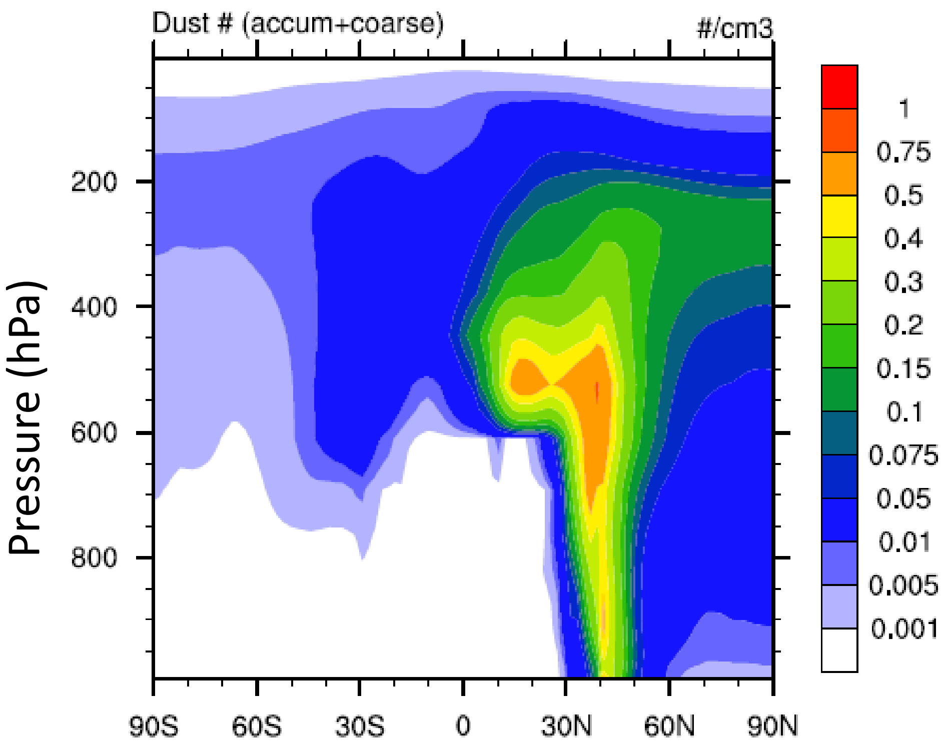
All Aitken mode sulfate

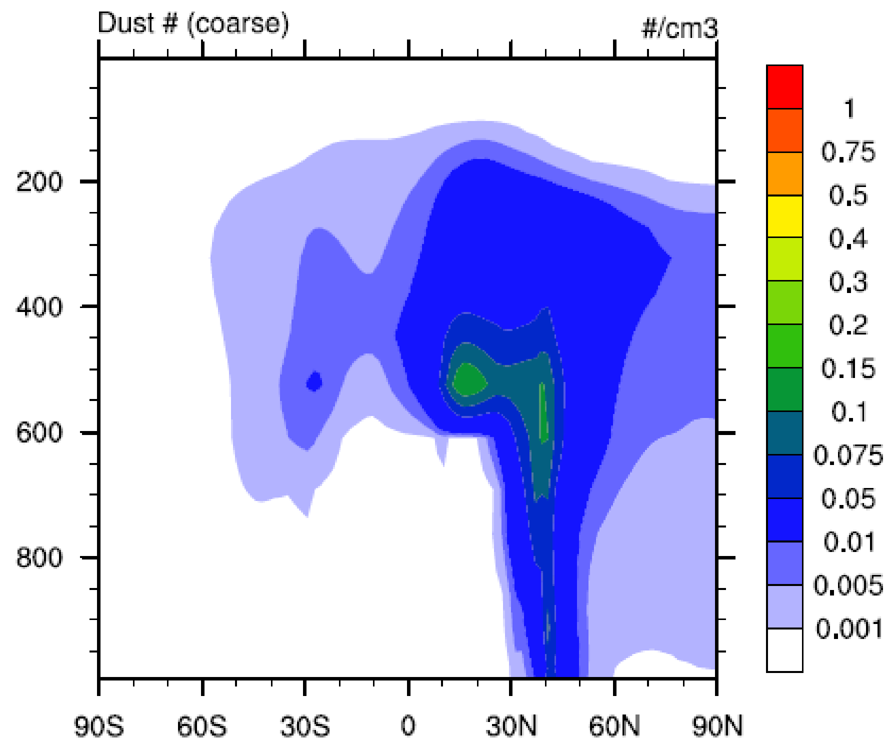


Aitken mode sulfate with D > 0.1 um

1. **Note that different scales are used in left and right graphs.**
2. **The sulfate number is about 1-2 order larger in the left graph.**

Background sulfate/dust numbers used in LP scheme





Dust # (Accumulation + coarse)

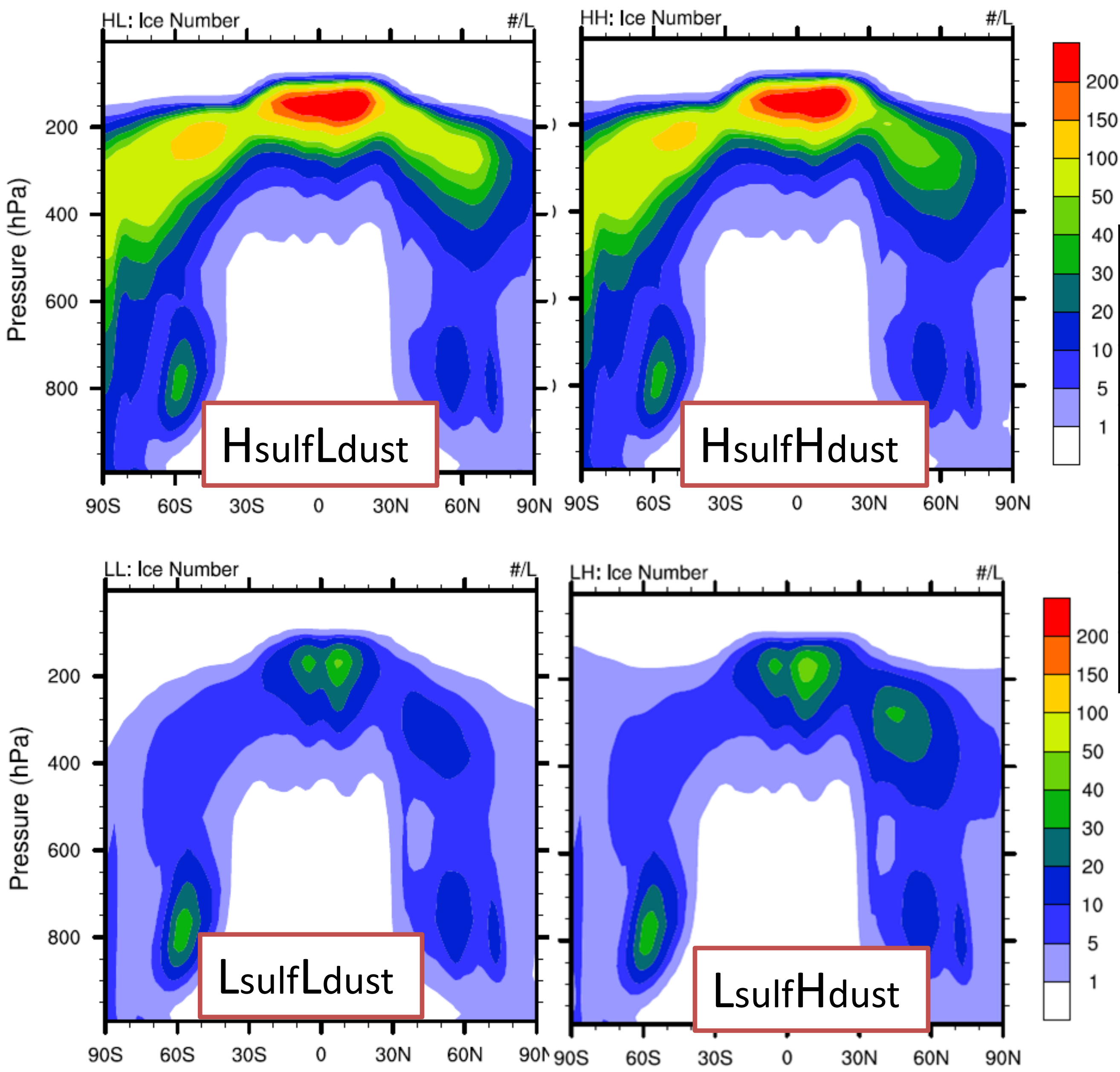
Dust # (coarse mode only)

Case set-up

4 combinations of background sulfate and dust numbers used in the ice nucleation.

	Case	Sulfate #	Dust #
1	HL	High	Low
2	HH	High	High
3	LL	Low	Low
4	LH	Low	High

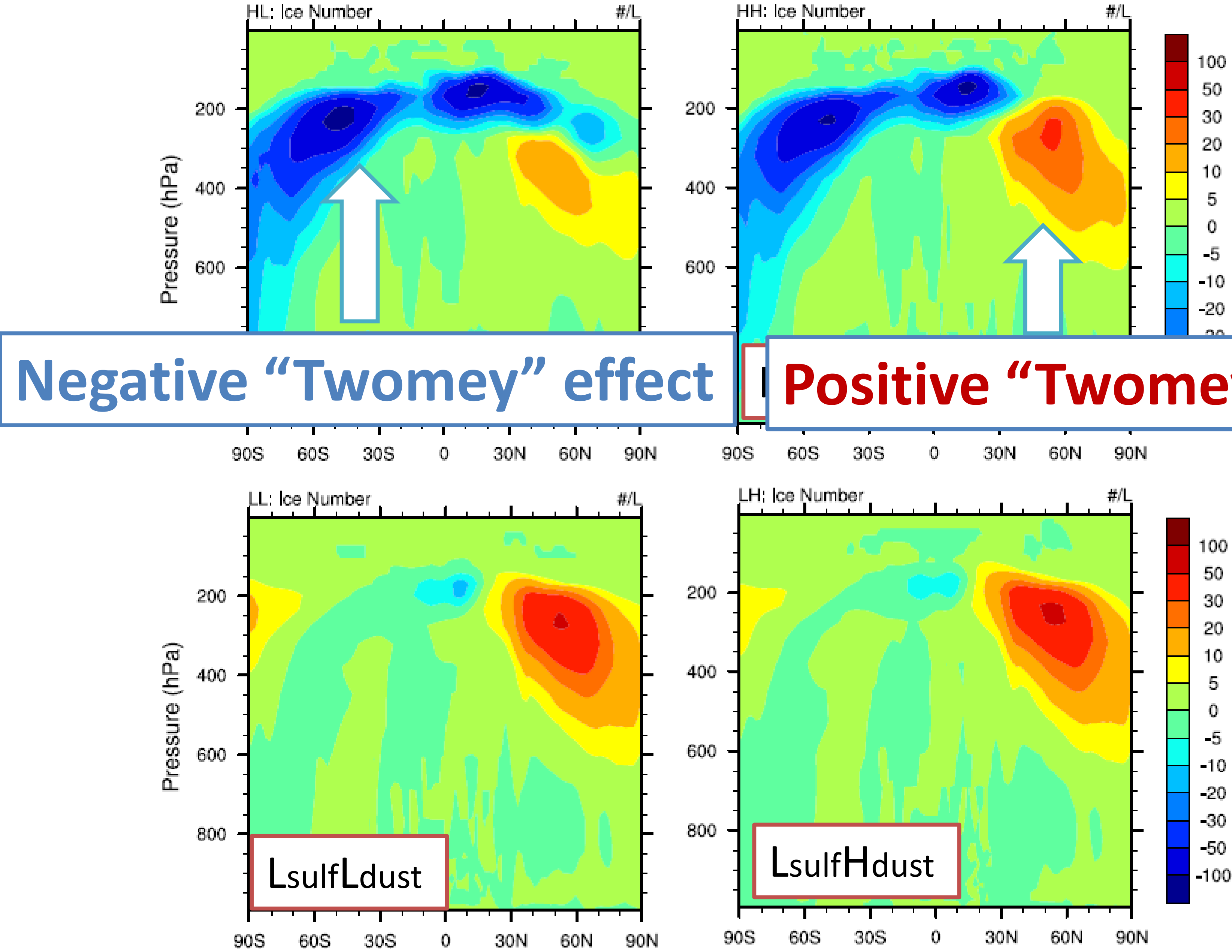
Base cases: Zonal mean ice number



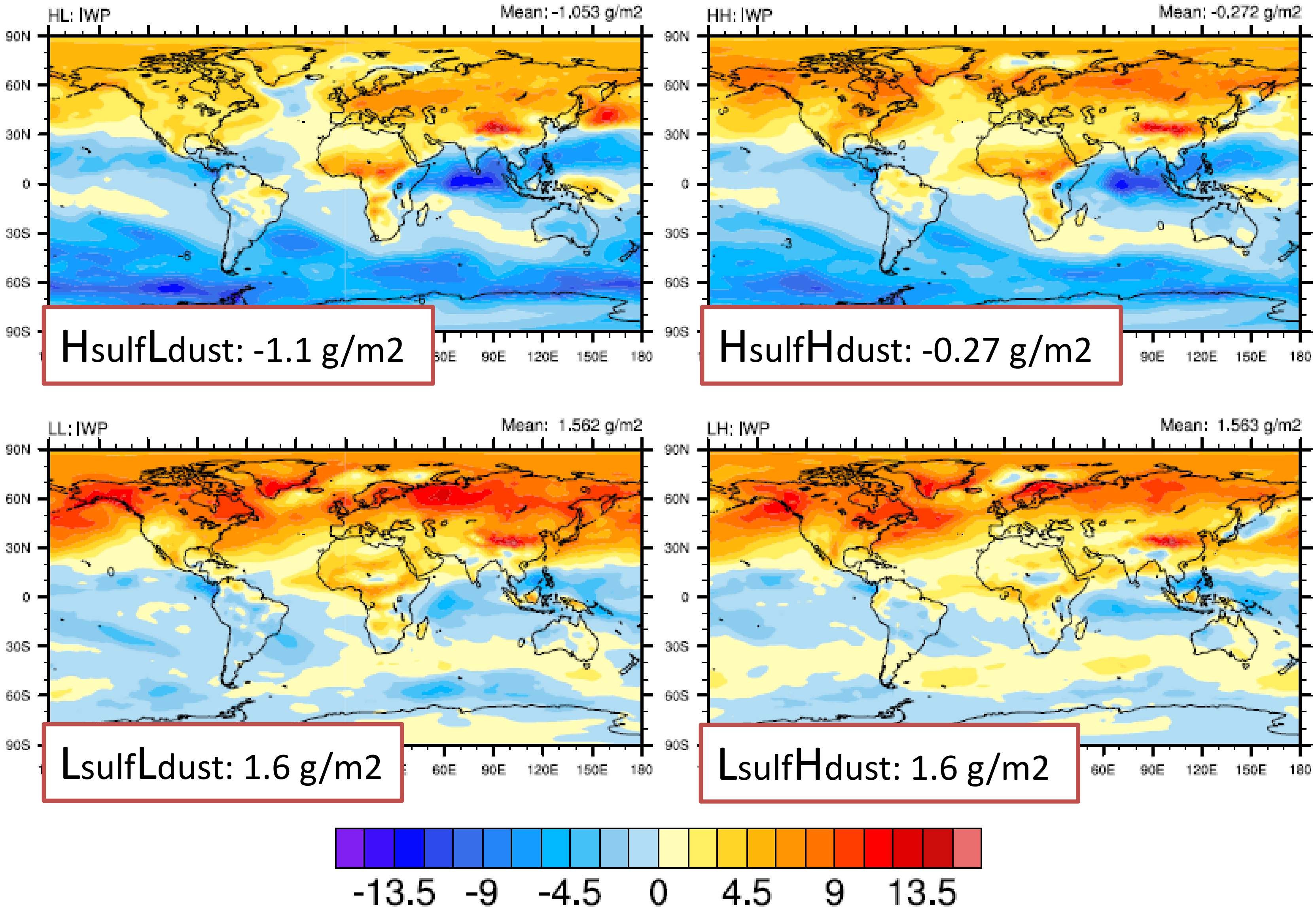
Key cloud properties

base cases	SWCF ($W\ m^{-2}$)	LWCF ($W\ m^{-2}$)	IWP ($g\ m^{-2}$)	LWP ($g\ m^{-2}$)
$H_{sulf}L_{dust}$	-61.1	33.5	21.4	47.5
$H_{sulf}H_{dust}$	-60.2	32.6	20.9	47.0
$L_{sulf}L_{dust}$	-52.1	24.1	17.7	44.6
$L_{sulf}H_{dust}$	-52.8	25.0	18.1	45.0

20% cases - Effect on ice number

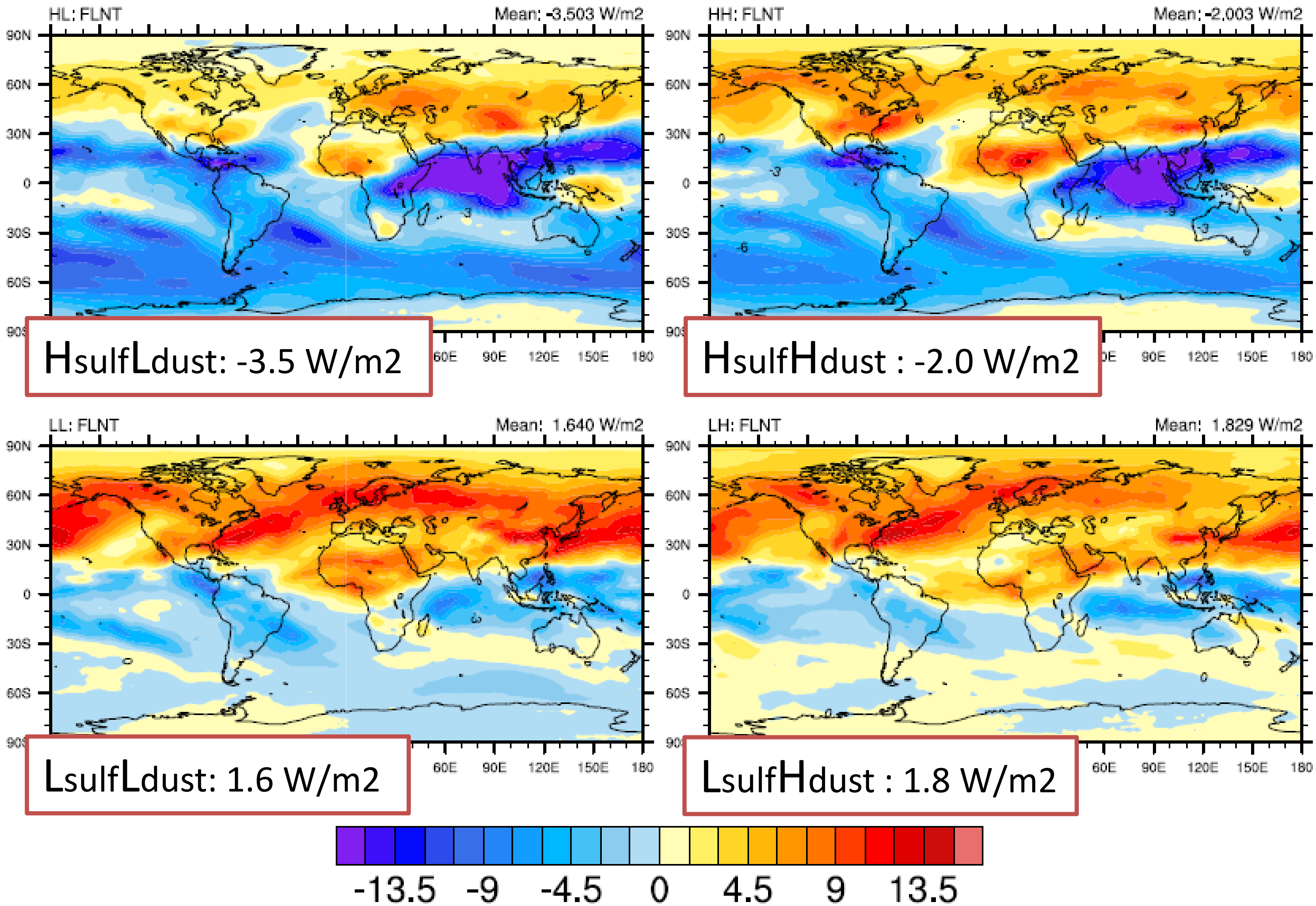


20% cases - Effect on ice water path



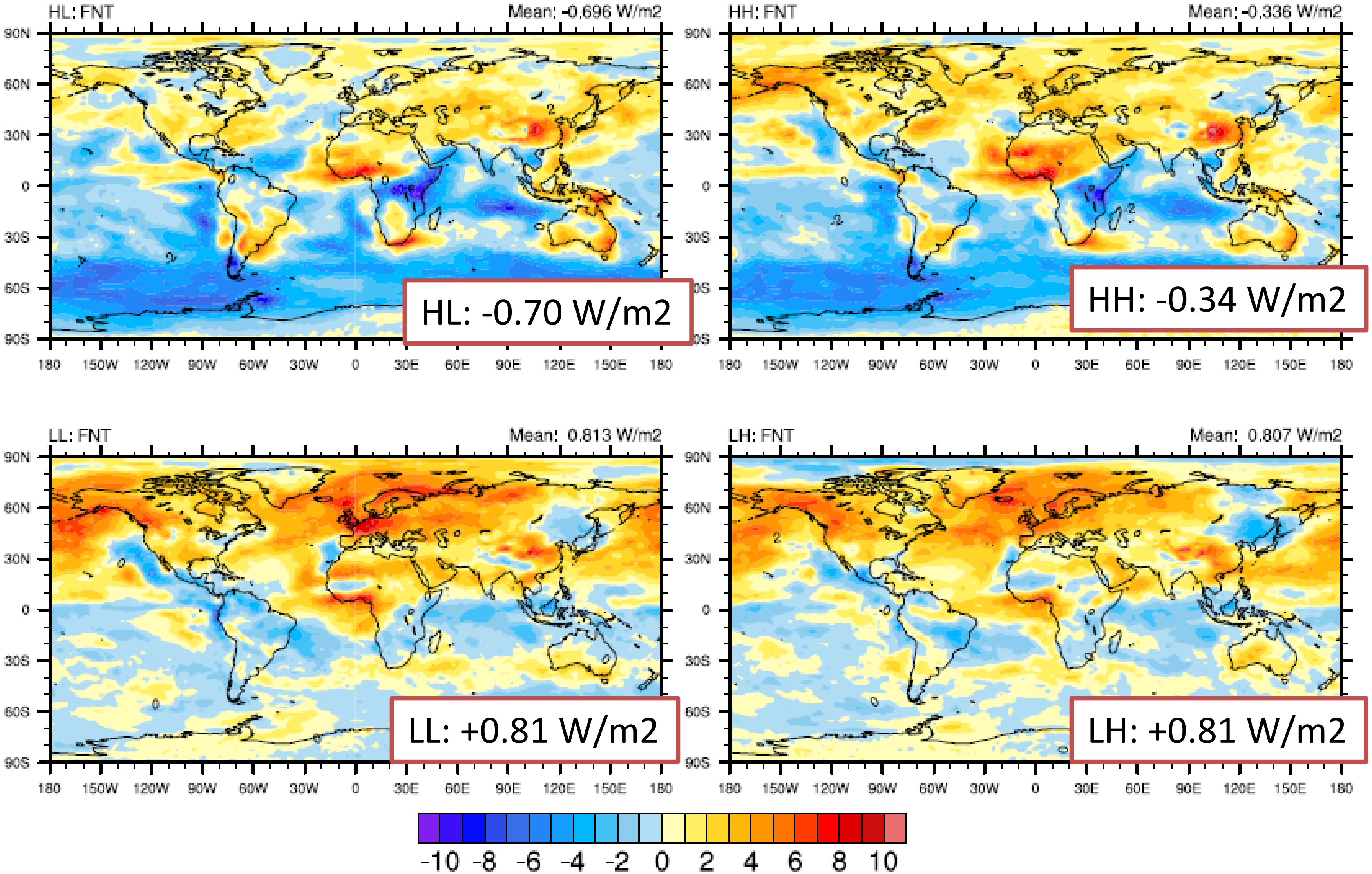
1. **Similar patterns : increase in NH, decrease in tropical oceans.**
2. **regional maganitude varies.**

20% cases - Effect on net long wave flux



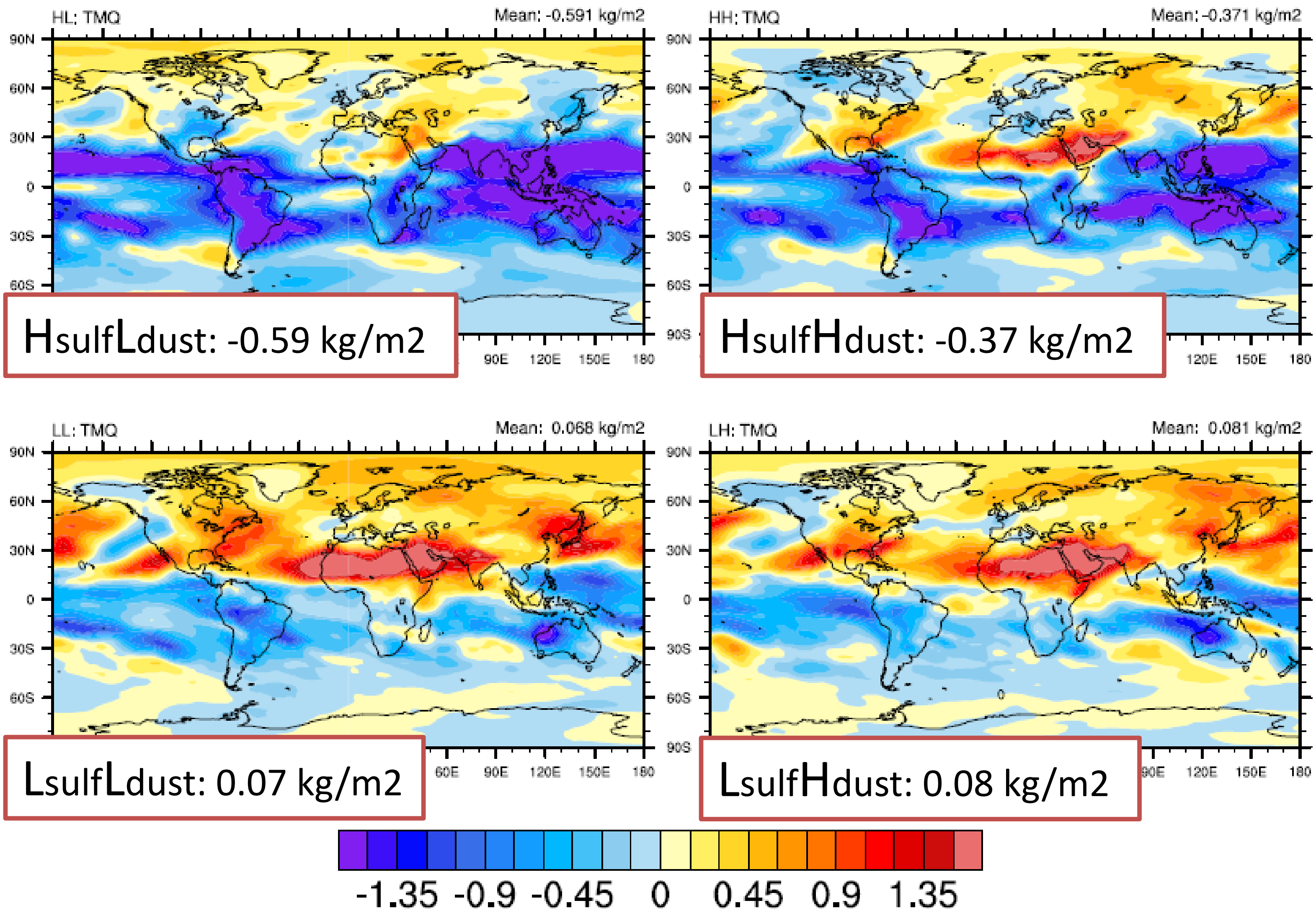
1. **Strongly correlated to the change of IWP.**
2. **regional maganitude varies.**

20% cases - Effect on total flux



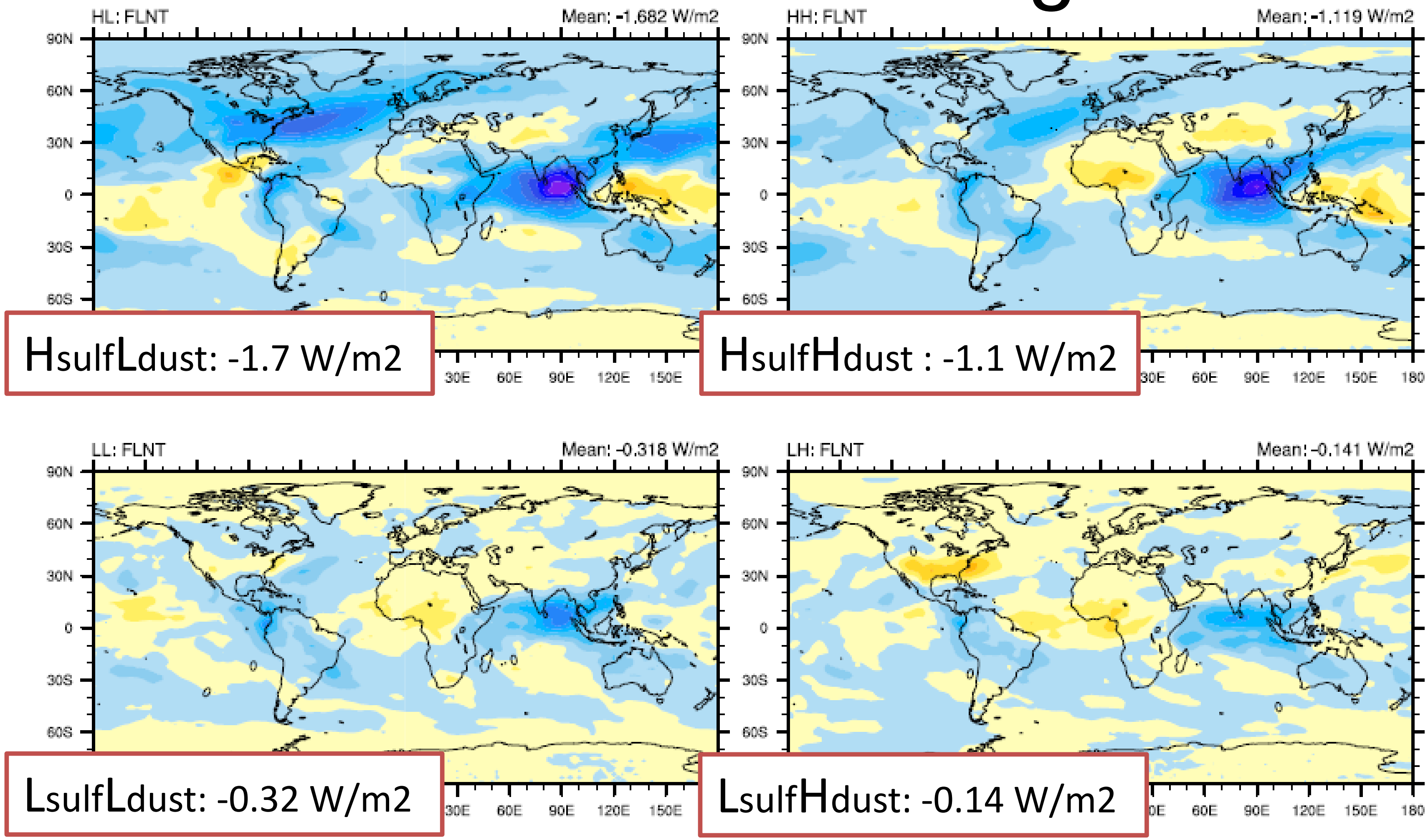
1. **Dominated by the change of long wave flux.**
2. **Negative forcing for high sulfate cases**
3. **Positive forcing for low sulfate cases**

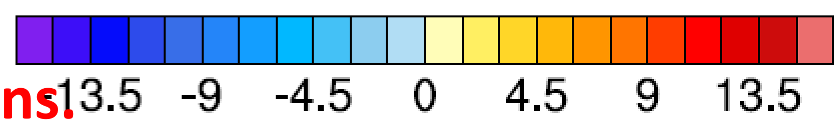
20% cases - Effect on hydrologic cycle: total water vapor



1. **Decreased temperature, precipitable water vapor in tropics.**
2. **Increased convection cloud fraction/convection precipitation.**
3. **Cleary sky cooling is not negligible.**

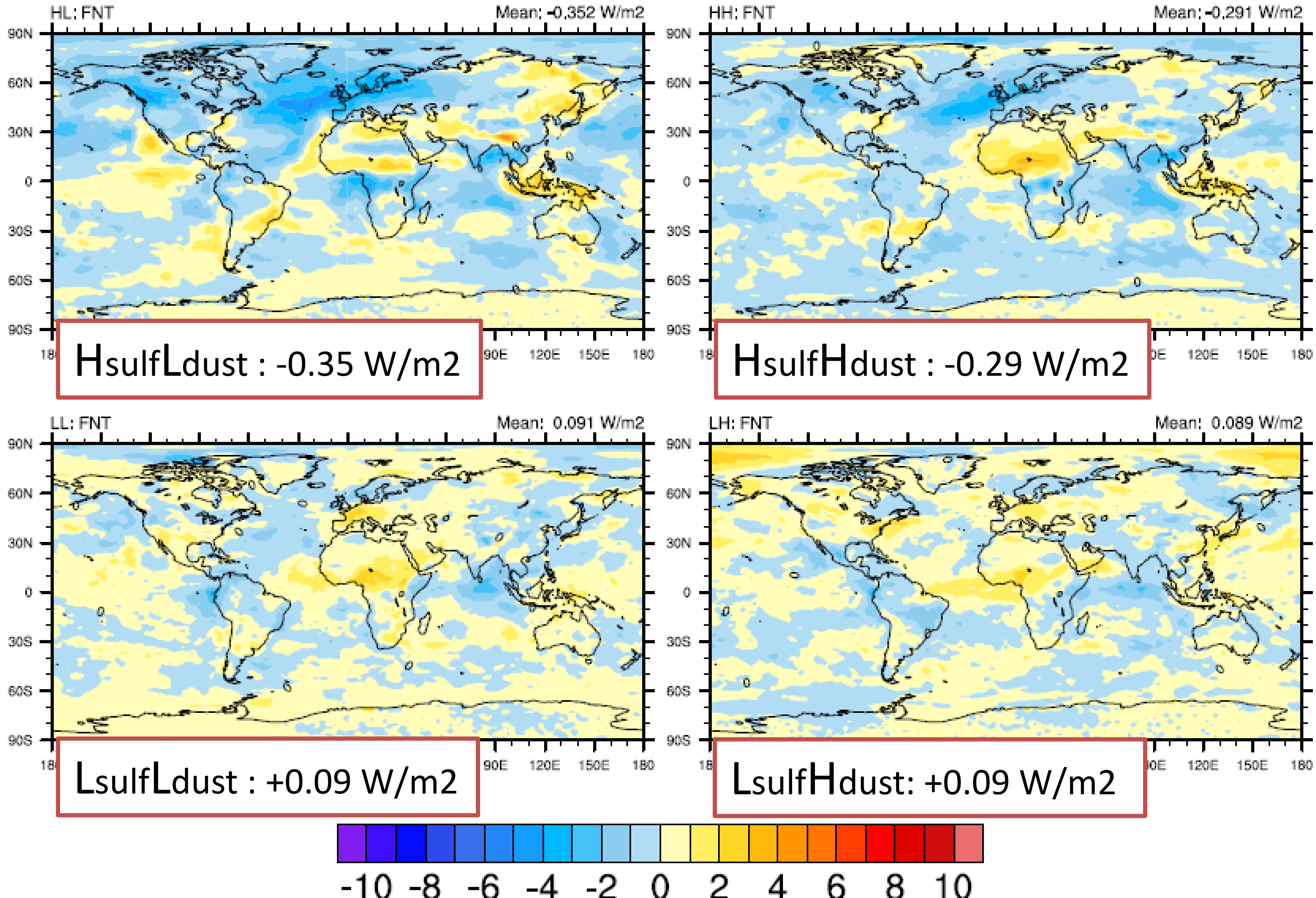
0.6 % cases - Effect on long wave flux





1. **50-year simulations.**
2. **Pass Student-t test with a confidence level of 90% in major cooling and warming regions.**

0.6 % cases - Effect on total forcing

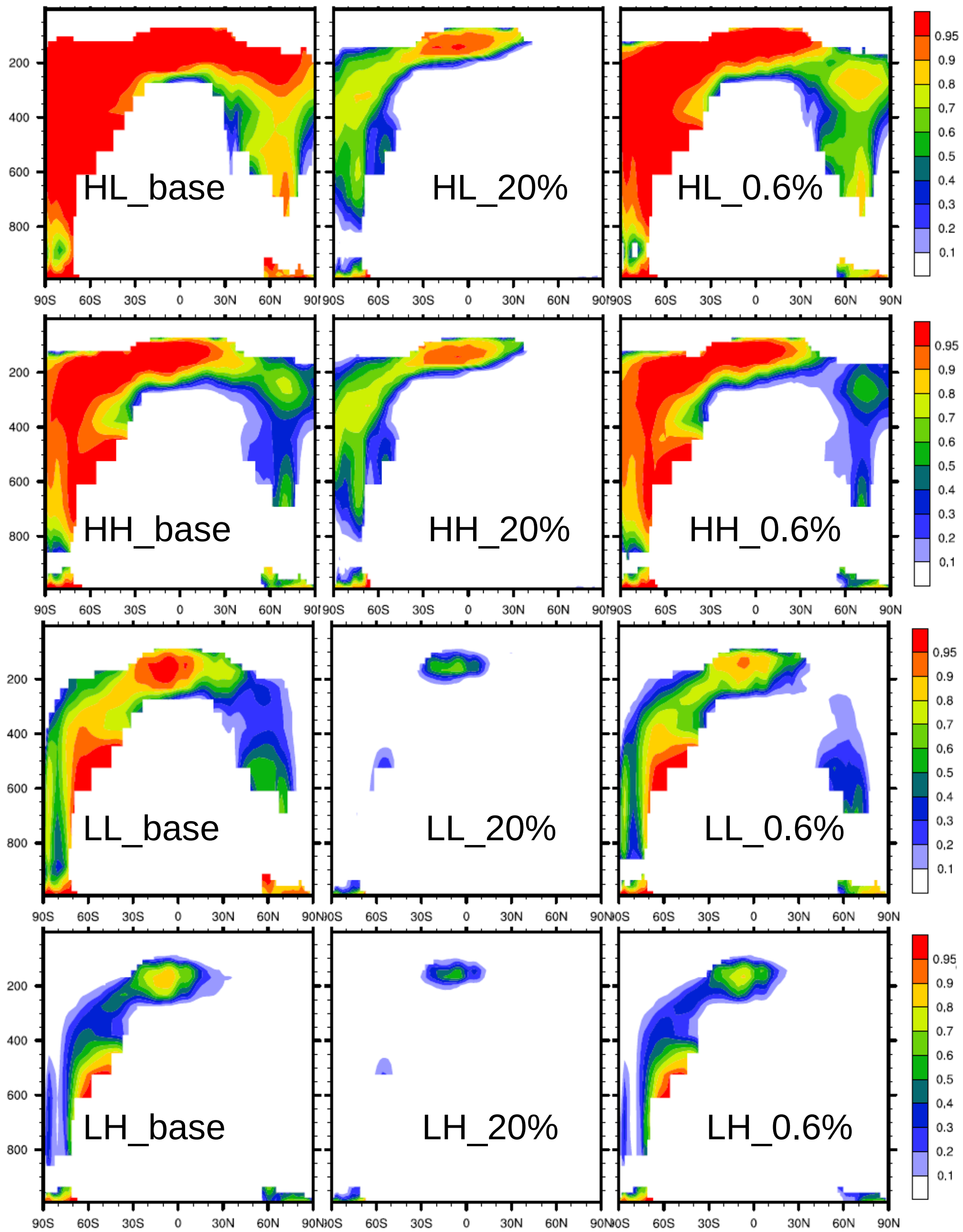


1. **Negative forcing for high sulfate cases**
2. **Positive forcing for low sulfate cases**

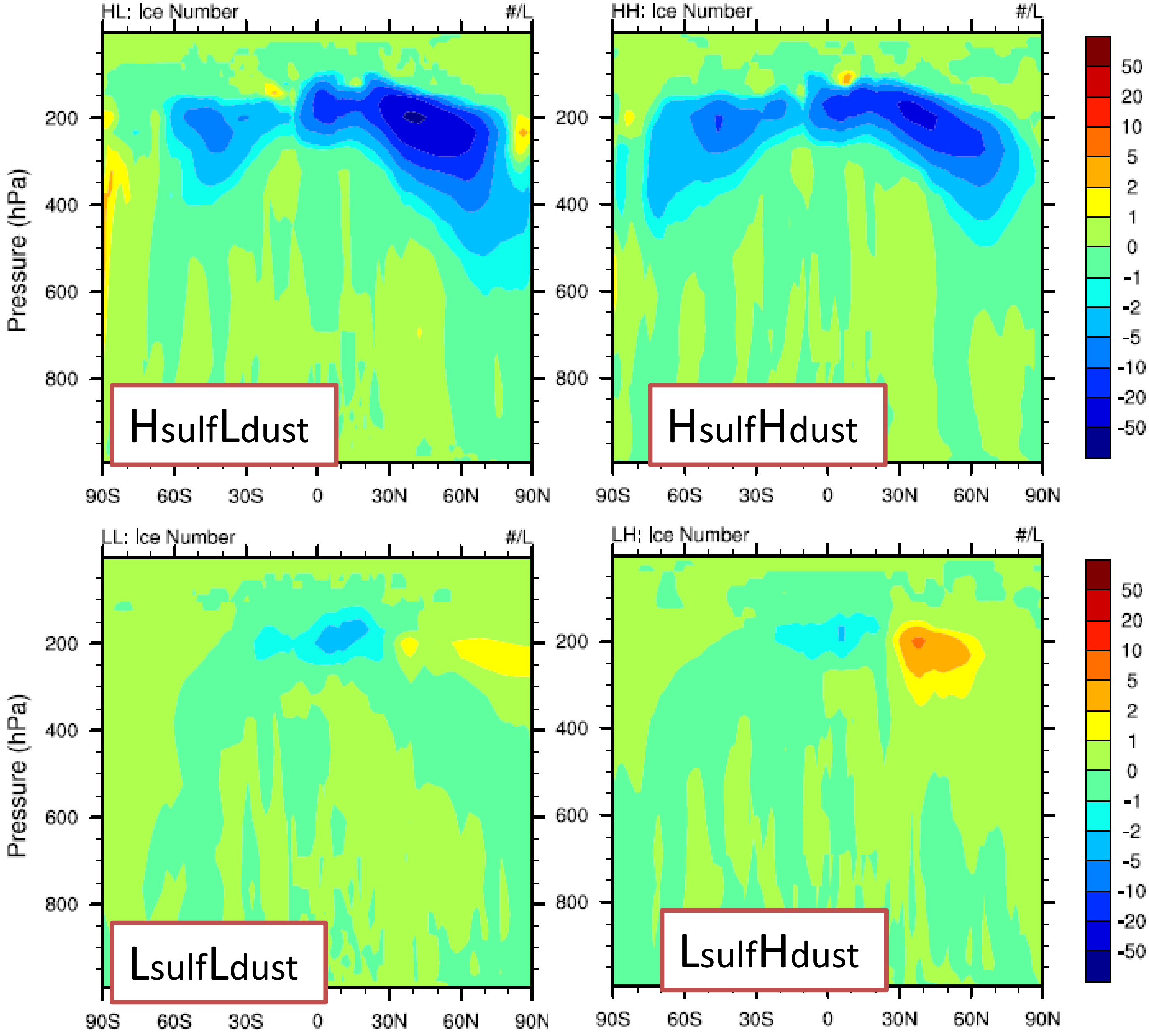
Conclusions

1. The global mean radiative forcing of aircraft soot on large-scale cirrus strongly depends on the background ice nucleation(ie., sulfate number). It ranges from -0.70 W/m2 to +0.81 W/m2.
2. For the default CAM5 case, it is +0.81 W/m2 (20% case) and +0.09 W/m2 (0.6% case).
3. Regional forcing is sensitive to the fraction of aircraft soot acting as IN.

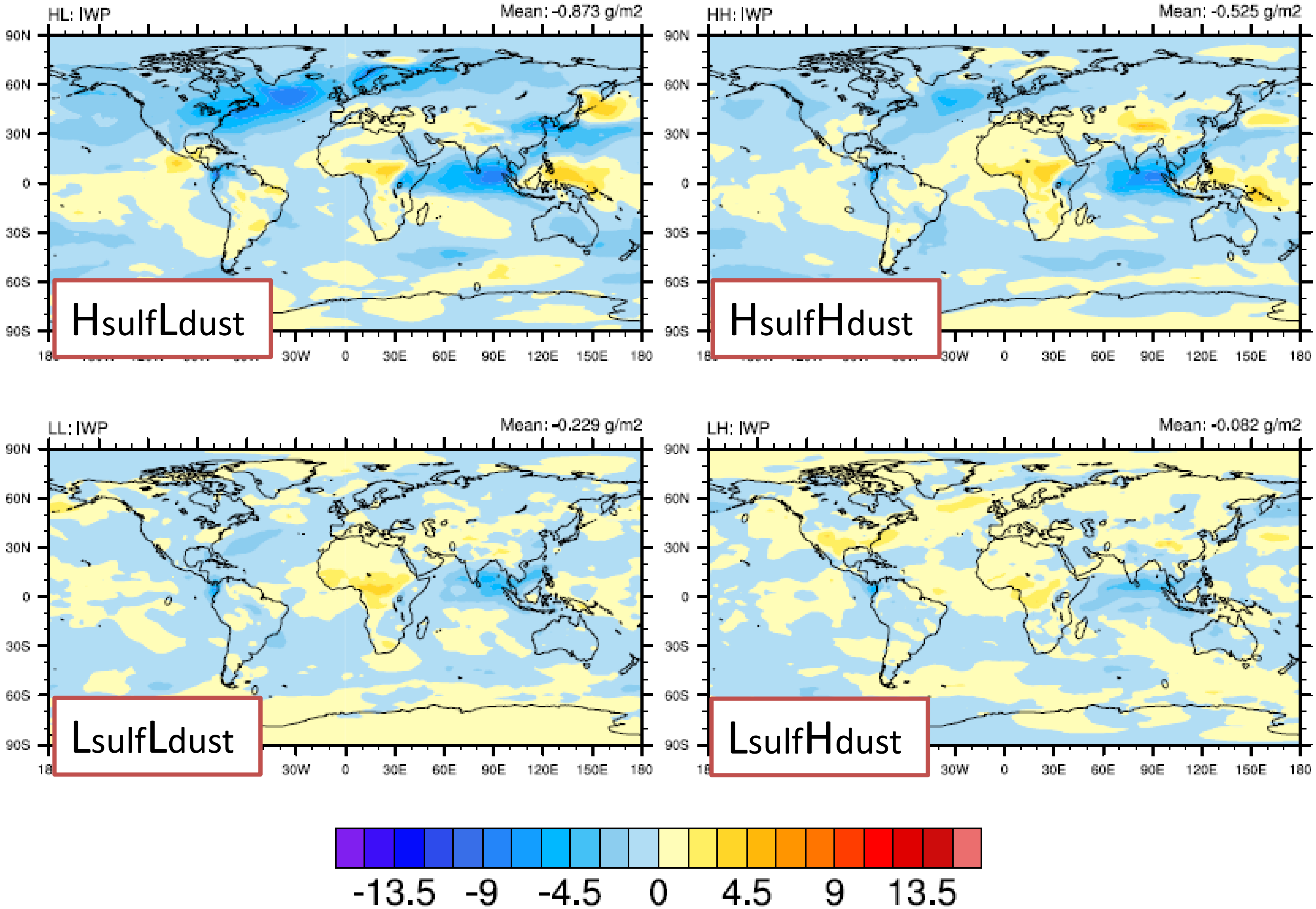
Zonal mean fraction of activated IN from homogeneous freezing



0.6 % cases - Effect on ice number



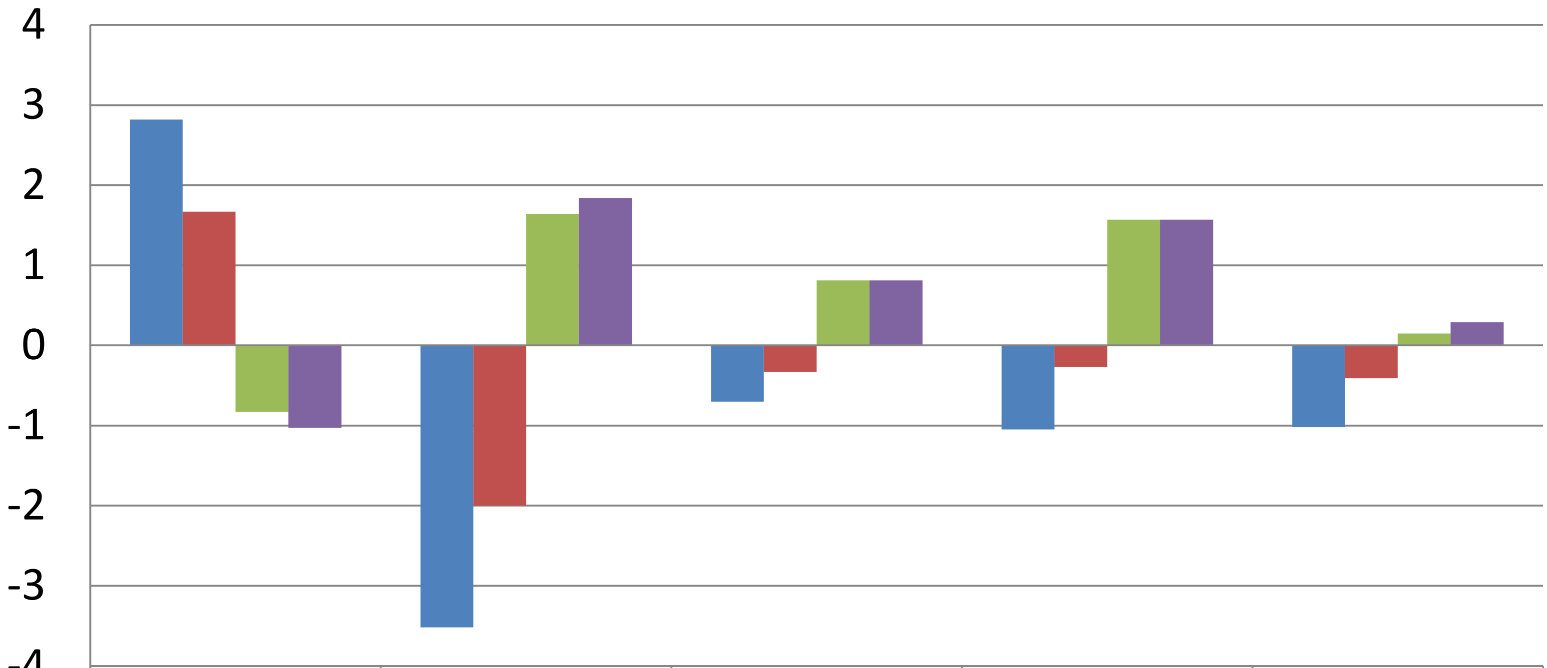
0.6 % cases - Effect on IWP



1. **Decreased IWP in tropical India ocean;**
2. **Increased IWP in central/north Africa.**

Summary 1- 20% cases

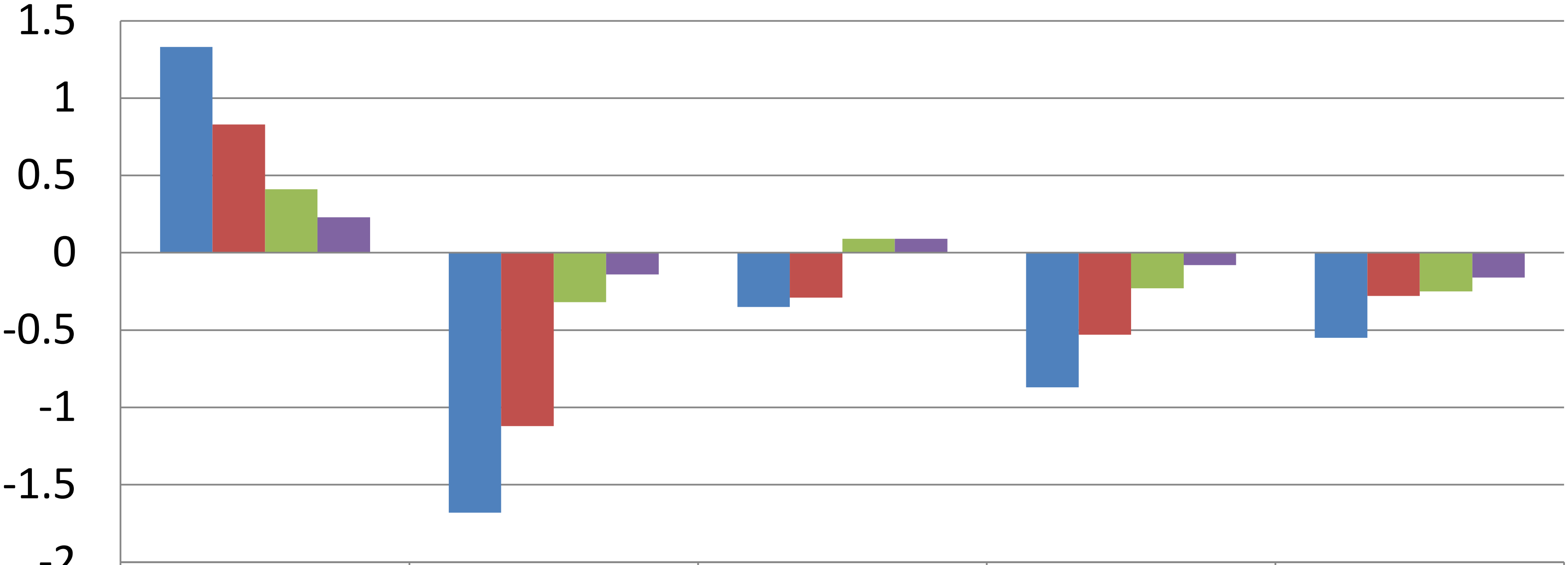
Change of radiative properties from 20% IN cases



	dFSNT	dFLNT	dFNT	dIWP	dLWP
HL	2.82	-3.52	-0.7	-1.05	-1.02
HH	1.67	-2	-0.33	-0.27	-0.41
LL	-0.83	1.64	0.81	1.57	0.15
LH	-1.03	1.84	0.81	1.57	0.29

Summary 2- 0.6% cases

Change of radiative properties from ~0.6% IN cases



	dFSNT	dFLNT	dFNT	dIWP	dLWP
HL	1.33	-1.68	-0.35	-0.87	-0.55
HH	0.83	-1.12	-0.29	-0.53	-0.28
LL	0.41	-0.32	0.09	-0.23	-0.25
LH	0.23	-0.14	0.09	-0.08	-0.16

20% IN cases	Wsub=0.2 m/s				Wsub=0.1 m/s			
	$H_{sulf}L_{dust}$	$H_{sulf}H_{dust}$	$L_{sulf}L_{dust}$	$L_{sulf}H_{dust}$	$H_{sulf}L_{dust}$	$H_{sulf}H_{dust}$	$L_{sulf}L_{dust}$	$L_{sulf}H_{dust}$
ΔCF	-0.09	0.06	1.04	0.83	0.64	0.80	1.08	0.83
ΔSWCF	2.88	1.76	-0.89	-1.08	2.31	1.42	-0.90	-0.90
ΔLWCF	-2.97	-1.70	1.92	1.91	-1.67	-0.62	1.98	1.72
ΔFNT	**-0.70**	**-0.33**	**0.81**	**0.81**	**0.11**	**0.65**	**0.83**	**0.79**
ΔFSNT	2.82	1.67	-0.83	-1.03	2.26	1.45	-0.87	-0.91
ΔFLNT	-3.52	-2.00	1.64	1.84	-2.15	-0.80	1.70	1.70
ΔFSNTC	-0.06	-0.09	0.06	0.05	-0.05	0.04	0.03	-0.02
ΔFLNTC	-0.55	-0.30	-0.27	-0.07	-0.47	-0.18	-0.28	-0.03
ΔIWP	-1.05	-0.27	1.57	1.57	-0.09	0.39	1.25	1.08
ΔLWP	-1.02	-0.41	0.15	0.29	-0.97	-0.50	0.25	0.24
ΔPRECT	0.08	0.06	-0.02	-0.03	0.05	0.03	-0.03	-0.03
ΔPRECC	0.09	0.07	0.00	-0.01	0.08	0.06	-0.01	-0.02
ΔPRECL	0.00	-0.01	-0.02	-0.02	-0.03	-0.03	-0.01	-0.01
ΔTMQ	-0.59	-0.37	0.07	0.08	-0.52	-0.35	0.11	0.14

0.6% IN cases	Wsub=0.2 m/s				Wsub=0.1 m/s			
	$H_{sulf}L_{dust}$	$H_{sulf}H_{dust}$	$L_{sulf}L_{dust}$	$L_{sulf}H_{dust}$	$H_{sulf}L_{dust}$	$H_{sulf}H_{dust}$	$L_{sulf}L_{dust}$	$L_{sulf}H_{dust}$
ΔCF	-0.23	-0.19	0.10	0.09	-0.25	0.03	0.09	0.10
ΔSWCF	1.36	0.85	0.42	0.21	1.43	0.84	0.28	0.12
ΔLWCF	-1.59	-1.04	-0.33	-0.12	-1.68	-0.82	-0.20	-0.02
ΔFNT	**-0.35**	**-0.29**	**0.09**	**0.09**	**-0.35**	**-0.02**	**0.13**	**0.15**
ΔFSNT	1.33	0.83	0.41	0.23	1.40	0.86	0.31	0.11
ΔFLNT	-1.68	-1.12	-0.32	-0.14	-1.75	-0.88	-0.18	0.04
ΔFSNTC	-0.03	-0.03	-0.01	0.02	-0.03	0.01	0.03	-0.01
ΔFLNTC	-0.10	-0.07	0.01	-0.02	-0.07	-0.06	0.02	0.05
ΔIWP	-0.87	-0.53	-0.23	-0.08	-0.76	-0.31	-0.15	-0.01
ΔLWP	-0.55	-0.28	-0.25	-0.16	-0.54	-0.27	-0.14	-0.06
ΔPRECT	0.03	0.02	0.00	0.00	0.04	0.02	0.01	0.00
ΔPRECC	0.03	0.02	0.01	0.00	0.05	0.03	0.01	0.00
ΔPRECL	0.00	0.00	0.00	0.00	-0.01	-0.01	-0.01	0.00
ΔTMQ	-0.25	-0.16	-0.09	-0.05	-0.27	-0.17	-0.08	-0.04