# Cirrus cloud radiative forcing on surface-level shortwave and longwave irradiances at regional and global scale

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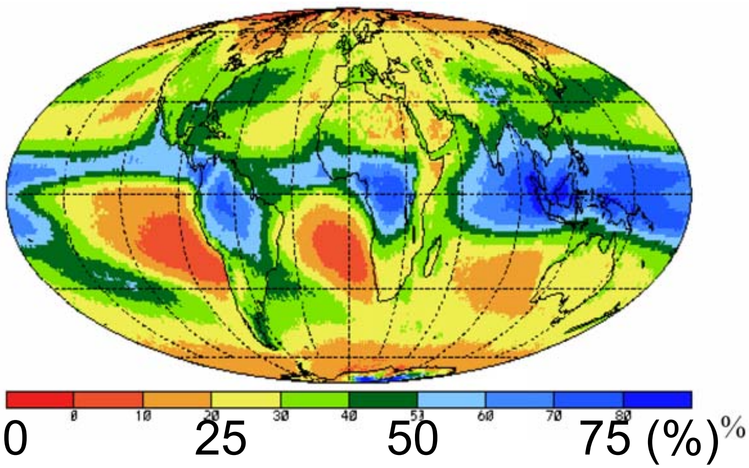
# Motivation for this study

Cirrus average cloud fraction



Stubenrauch et al. (2006)

Importance of cirrus cloud cover at global scale

Optically thin cirrus not included in historical climatologies, hence their radiative forcing is not accounted for

Tenuous effects on radiation can be difficult to measure: need accurate references to quantify impact

Effect of cirrus clouds (and contrails) on: BL dynamics, daily temperature range, global dimming and brightening

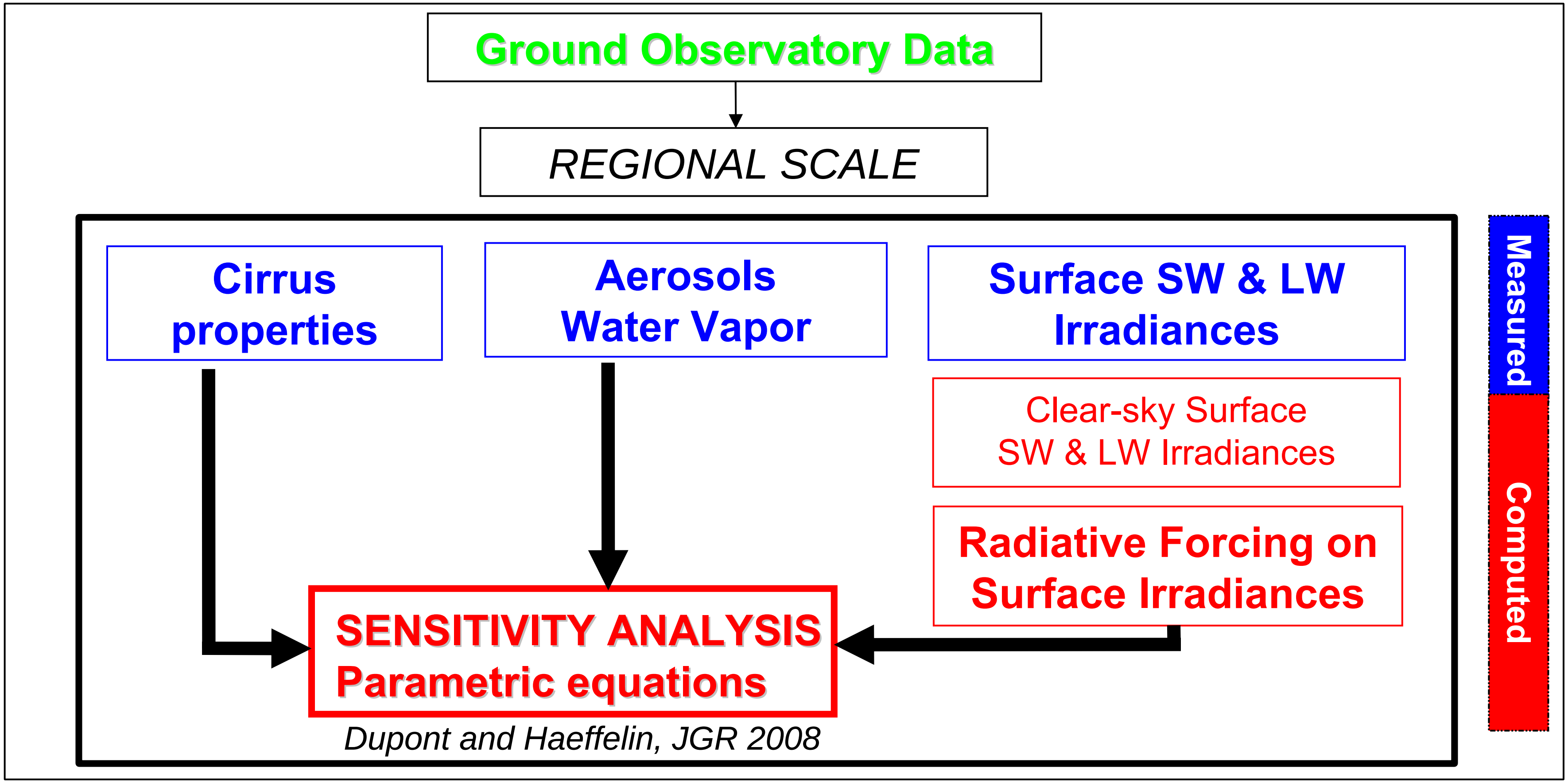
**⇨ This study focuses on radiative forcing of non-opaque (OD<3) cirrus clouds on surface-level irradiances**

# Outline

- Method to estimate radiative forcing
- Cloud and radiation measurements used in this study
- Clear-sky irradiance references
- Sensitivity of cirrus radiative forcing to aerosols and water vapor
- Results at the global scale
- Conclusions

# Deriving cirrus radiative forcing

## Methodology



Ground Observatory Data

*REGIONAL SCALE*

**Cirrus properties**

**Aerosols**
**Water Vapor**

**Surface SW & LW Irradiances**

Clear-sky Surface
SW & LW Irradiances

**Radiative Forcing on Surface Irradiances**

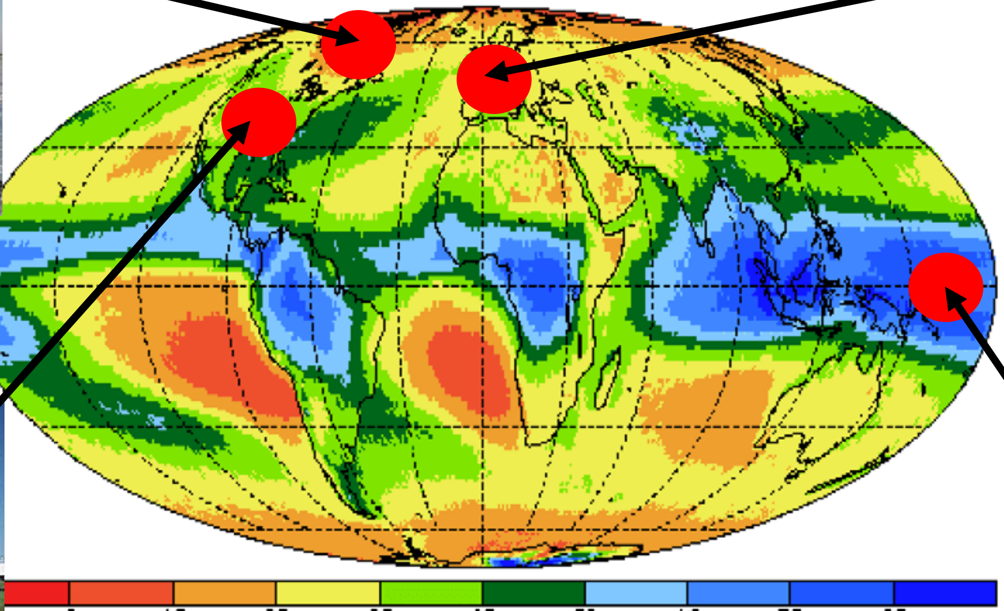
**SENSITIVITY ANALYSIS**
**Parametric equations**

*Dupont and Haeffelin, JGR 2008*

⇨ **Develop parametric representations of cirrus radiative forcing on surface-level irradiances and its sensitivity to atmospheric properties.**

# Ground-based observatories

ARM NSA Barrow
71°N/-156°E
Rural / Arctic



*Cirrus Cloud Cover (%) from Stubenrauch et al. 2006*

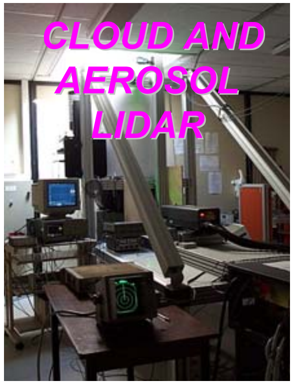
SIRTA Palaiseau
48°N/2°E
Urban / Oceanic

ARM SGP Lamont
36°N/-97°E
Rural / Cont.

ARM TWP Nauru
0°N/167°E
Island / Oceanic

**⇨ Data source from 4 observatories: large range of cirrus occurrence, atmospheric moisture and aerosol load.**

# Measurements and data



| | ***SIRTA Palaiseau*** | ***ARM SGP Lamont*** | ***ARM TWP Nauru*** | ***ARM NSA Barrow*** |
|---|---|---|---|---|
| **Period** | 2002 – 2007 | 1998 – 2003 | 2003 | 2003-2005 |
| **RADIATIVE FLUXES** (SW, LW) | Pyranometer, pyrgeometer, pyrheliometer | | | |
| **WATER VAPOR** (integrated water path) | Sun-photometer, GPS | Microwave radiometer | | |
| **AEROSOLS** (optical thickness) | Sun-photometer | | | |
| **CLOUDS** (base and top altitude) | Backscatter lidar | Raman Lidar | Micro-pulse lidar | |
| **Temperature, humidity** | Ground station, radiosonding | | | |

**⇨ Colocated measurements of surface radiation and atmospheric properties**

# Clear-sky irradiance references

$\mathrm{CRF}_{SW} = \mathrm{SW}_{measured} - \mathrm{SWCSM}$ $\quad$ $\mathrm{CRF}_{LW} = \mathrm{LW}_{measured} - \mathrm{LWCSM}$

## ShortWave Clear-Sky Model (SWCSM)

$$\mathrm{SWCSM} = \underbrace{a \times \cos(\mathrm{SZA})^{b} \times c^{1/\cos(\mathrm{SZA})}}_{\text{[Dutton et al. 2001]}} + \underbrace{\Phi_{(\mathrm{AOT},\ \mathrm{IWV})}}_{\text{Corrective function}}$$

**a** : solar constant adjusted for the Earth-Sun distance for each site

**b**, **c** : constants adjusted on clear-sky atmosphere and correspond to average scattering of atmosphere for each site

$\Phi$: accounts for fast variations in AOT and IWV

**Mean std error < 4 W / m²**

## LongWave Clear-Sky Model (LWCSM)

$$\mathrm{LWCSM} = \frac{\overbrace{\alpha \times (e/T)^{1/7}}^{\varepsilon\ \text{Brutsaert}}}{\Gamma_{(e,\ T,\ IWV)}} \times \sigma \times \left[\frac{T}{\Pi_{(T)}}\right]^{4}$$

*[Dupont et al., 2008]*

**T** : 2m-height temperature (K)

**e** : water vapor pressure near the surface (hPa)

$\sigma$ : $5.67 \times 10^{-8}$ W m$^{-2}$ K$^{-4}$

$\alpha$ : constant adjusted on clear-sky periods

$\Gamma$ : proxy for vertical distribution of humidity

$\Pi$ : proxy for thermal inertia of atmosphere

**Mean std error < 3 W / m²**

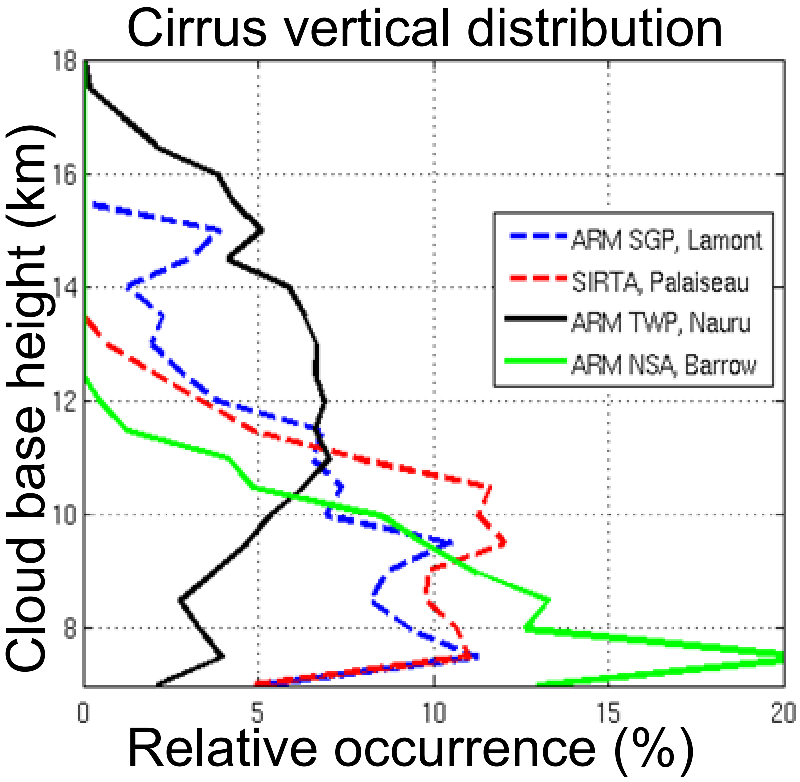
⇨ **Clear-sky parametric models are fitted to observed data**

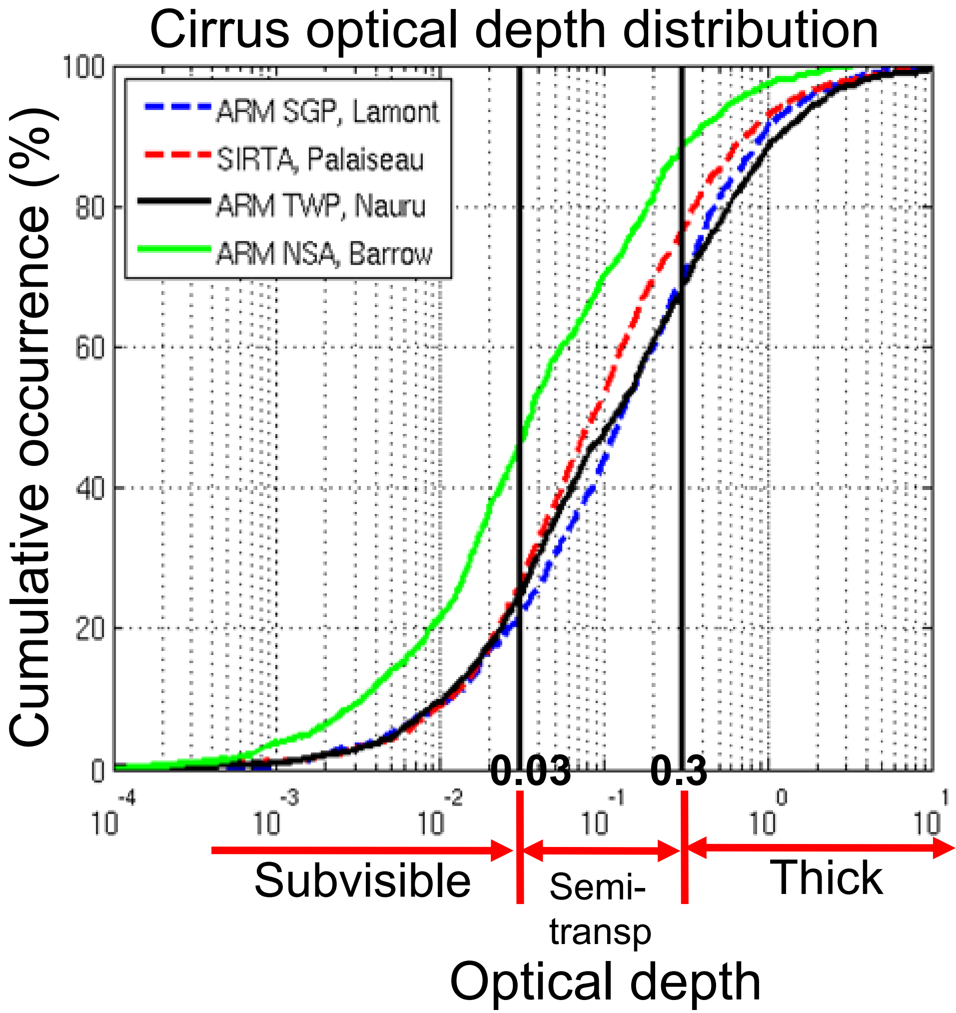
⇨ **Clear-sky data are identified by SW + LW + Lidar detection algorithms**

(Long and Ackerman 2000, Dürr and Philipona 2004, Morille et al. 2007)

# Cirrus properties

## Cirrus cloud occurrence, height and optical depth

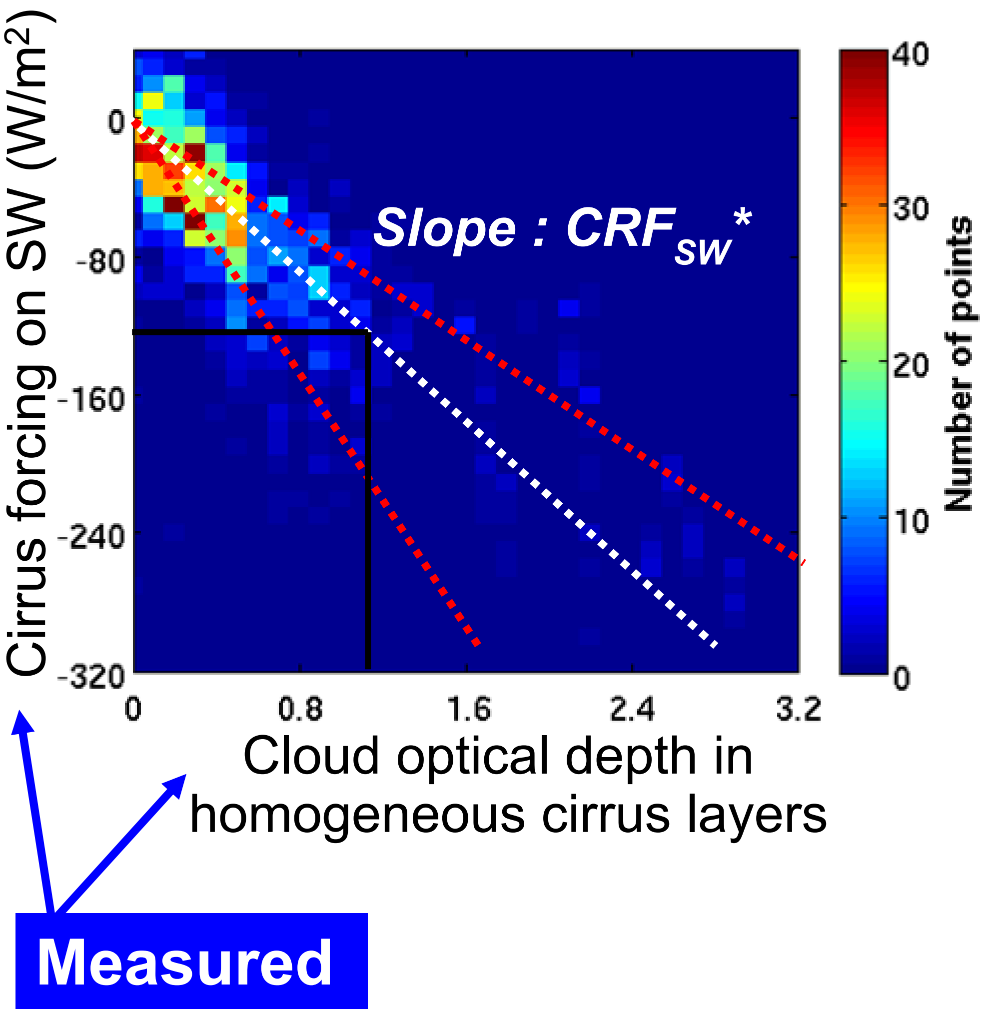




- ⇨ **Mean occurrence range from 10% in Arctic to 80% in Tropics**
- ⇨ **Nearly 50% non-opaque cirrus have COD < 0.1**

# Cirrus forcing on surface SW irradiance

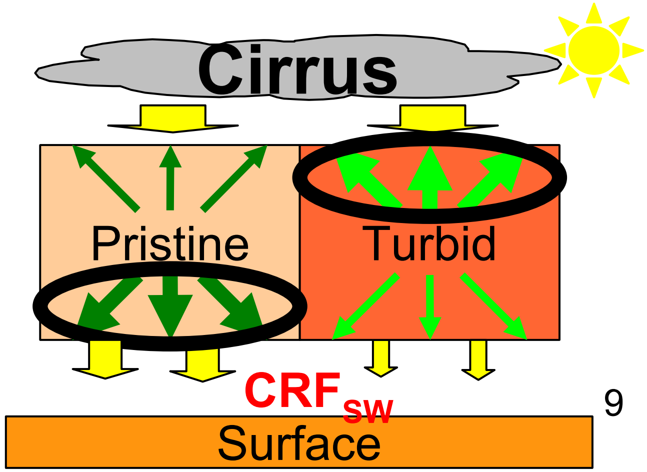
## Cirrus radiative forcing (cirrus-clear) as a function of cirrus properties, aerosols, water vapor, solar radiation



**For a cirrus with COD=1, the surface-level solar irradiance is reduced by about 120W/m$^2$**

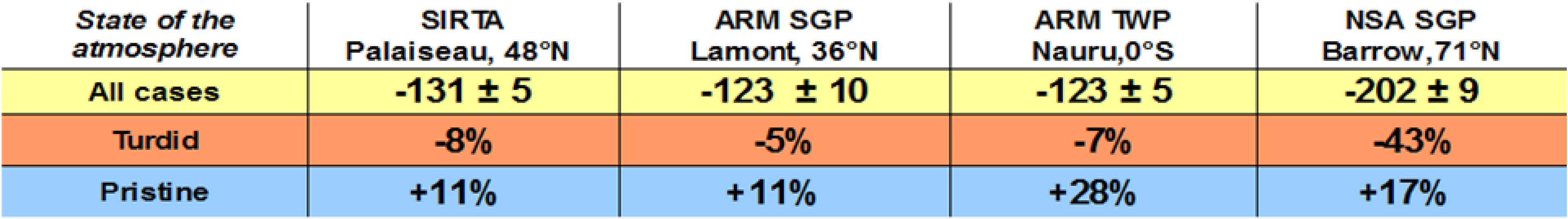
**Variability is associated with:**

- **Scattering by aerosols and water vapor**
- **Solar illumination geometry**
- **Cirrus microphysics**



# Cirrus forcing on surface SW irradiance

## Sensitivity of $CRF_{SW}^{*}$ to aerosols and water vapor ($W\ m^{-2}\ COT^{-1}$)



| *State of the atmosphere* | SIRTA<br>Palaiseau, 48°N | ARM SGP<br>Lamont, 36°N | ARM TWP<br>Nauru,0°S | NSA SGP<br>Barrow,71°N |
|---|---|---|---|---|
| All cases | -131 ± 5 | -123 ± 10 | -123 ± 5 | -202 ± 9 |
| Turdid | -8% | -5% | -7% | -43% |
| Pristine | +11% | +11% | +28% | +17% |

- ⇨ **Aerosols and water vapor act as a significant mask**
- ⇨ **Cirrus forcing is affected by -40% to +30%**

## Solar illumination geometry

As solar zenith angle increases, diffuse radiation increases but does not compensate for a general decrease in solar irradiance

- ⇨ **Cirrus forcing -40% to +30%**

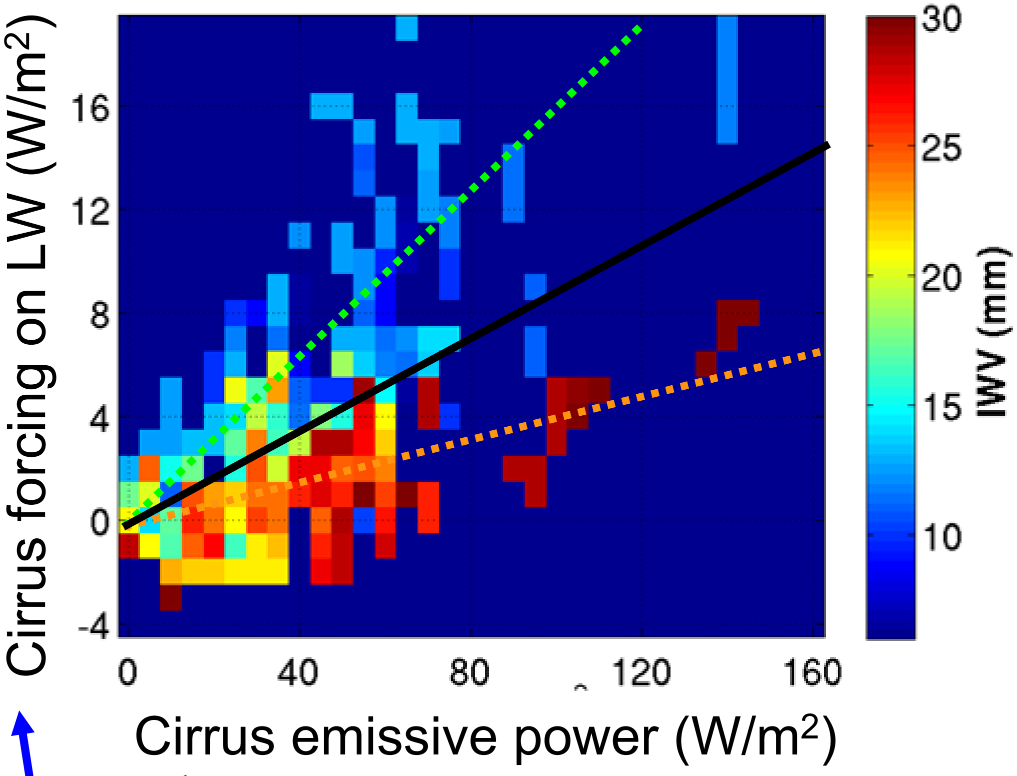
## Parametric equation cirrus radiative forcing

$$CRF_{SW} = [\ 90 \times (AOT+WVOT) + 0.0136 \times SZA^2 - 0.0612 \times SZA - 156.2\ ] \times COD$$

- ⇨ **Equation for large scale analysis**
- ⇨ **Accounts for solar geometry and atmospheric turbidity**

# Cirrus forcing on surface LW irradiance

## Cirrus radiative forcing as a function of water vapor

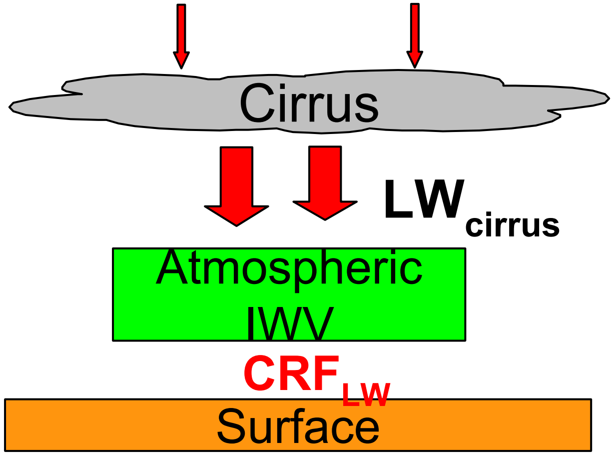


**Measured**

**For a cirrus of emissive power $100 W/m^2$, about $10 W/m^2$ reaches the surface**

**Variability is associated with:**

- **absorption by water vapor**



# Cirrus forcing on surface LW irradiance

## Sensitivity of $CRF_{LW}$* to water vapor (%)

| *State of the atmosphere* | SIRTA<br>Palaiseau, 48°N | ARM SGP<br>Lamont, 36°N | ARM TWP<br>Nauru,0°S | NSA SGP<br>Barrow,71°N |
|---|---|---|---|---|
| All cases | 12 ± 3 | 8 ± 2 | 1 ± 2 | 17 ± 3 |
| Wet | -17% | -13% | -7% | -24% |
| Dry | +11% | +13% | +50% | +18% |

- ⇨ Weak IR transmission (quasi-opaque) in Tropics (1%)
- ⇨ Strong IR transmission IR in Arctic (20%)

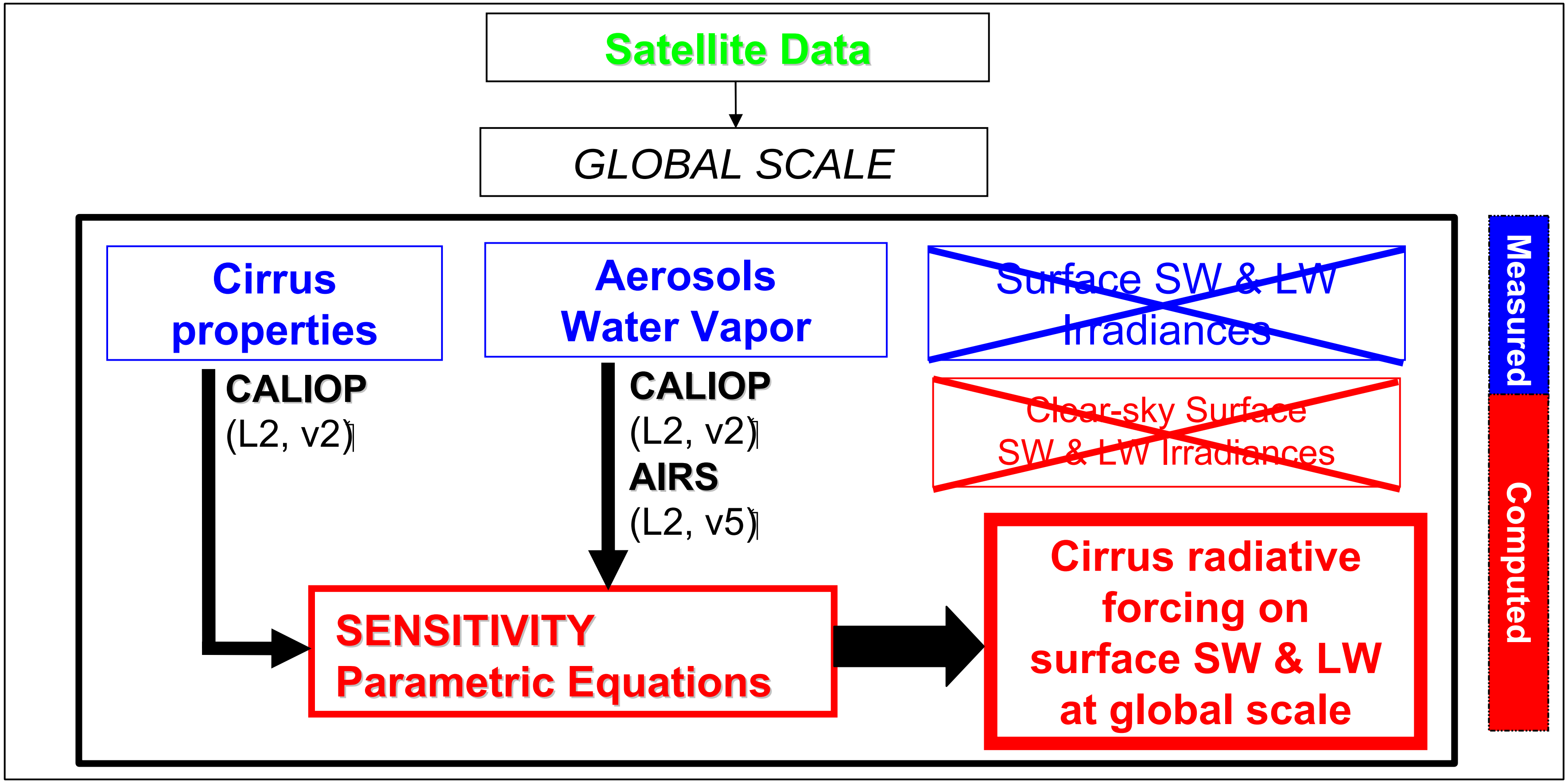
## Parametric equation of cirrus LW radiative forcing:

$$\boxed{CRF_{LW} = [\ 2.95 \times WVOT^2 - 2.0 \times WVOT + 0.3\ ] \times LW_{cirrus}}$$

- ⇨ Equation for large scale analysis
- ⇨ Cirrus IR signature on ground driven by water vapor

# Cirrus radiative forcing at the global scale

## Methodology



**Satellite Data**

*GLOBAL SCALE*

**Cirrus properties**

**CALIOP**
(L2, v2)

**Aerosols**
**Water Vapor**

**CALIOP**
(L2, v2)
**AIRS**
(L2, v5)

~~Surface SW & LW Irradiances~~

~~Clear-sky Surface SW & LW Irradiances~~

**SENSITIVITY**
**Parametric Equations**

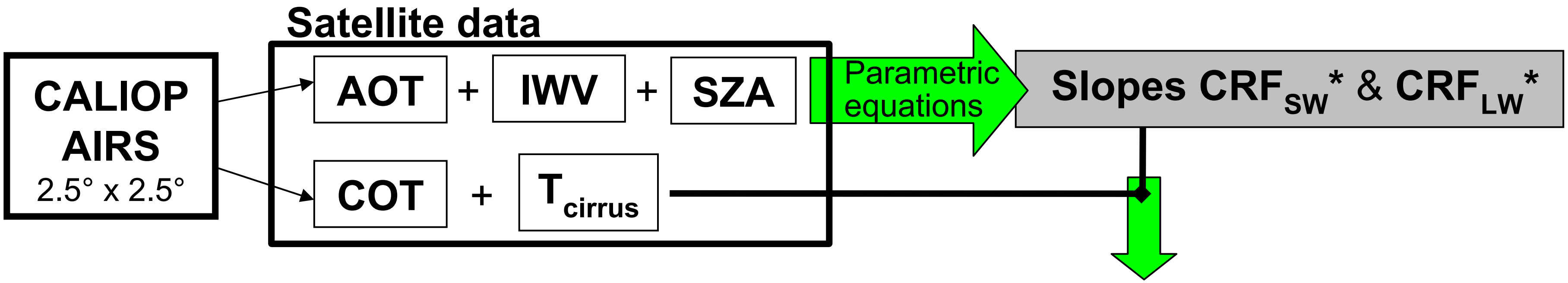
**Cirrus radiative forcing on surface SW & LW at global scale**

**Measured**

**Computed**

**⇨ Use cirrus and atmospheric properties from satellite data as input to parametric equation to compute cirrus radiative forcing**

# Consistency check: CRF computed from satellite vs ground-based data



**Satellite data**

CALIOP
AIRS
2.5° x 2.5°

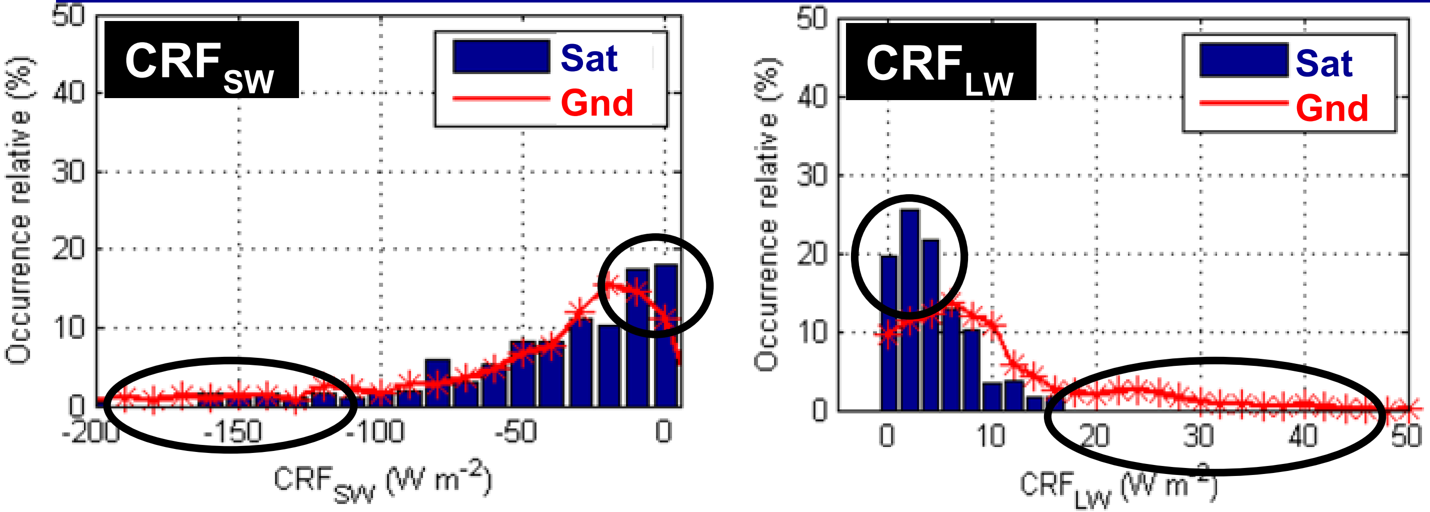
AOT + IWV + SZA

COT + $T_{cirrus}$

Parametric equations

Slopes $CRF_{SW}$* & $CRF_{LW}$*

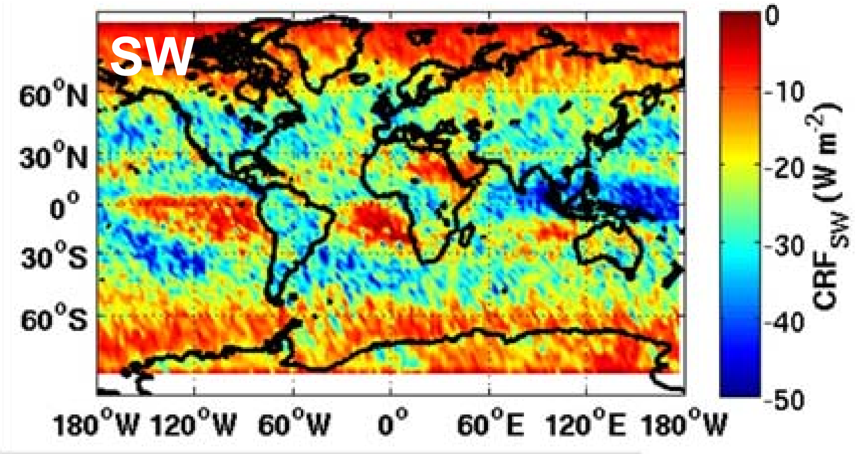
**CRF above each ground site computed from satellite data**



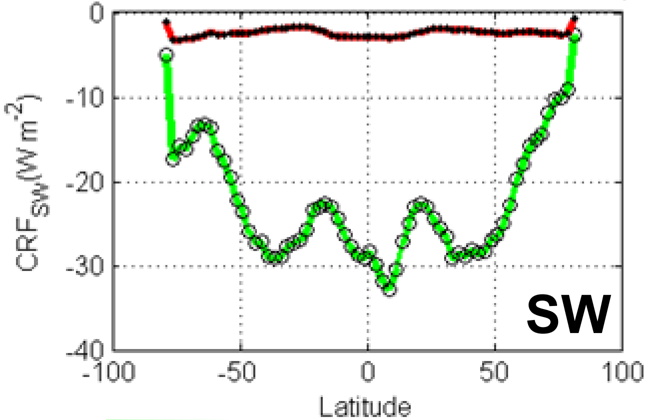
⇨ **Sources of discrepancy: (1) parametric equations, (2) low bias in cirrus OD in Caliop compared to ground-based lidar, (3) PDFs of IWV and AOD narrower in satellite data.**

# *Cirrus radiative forcing at the global scale*

## Instantaneous forcing when cirrus clouds are present

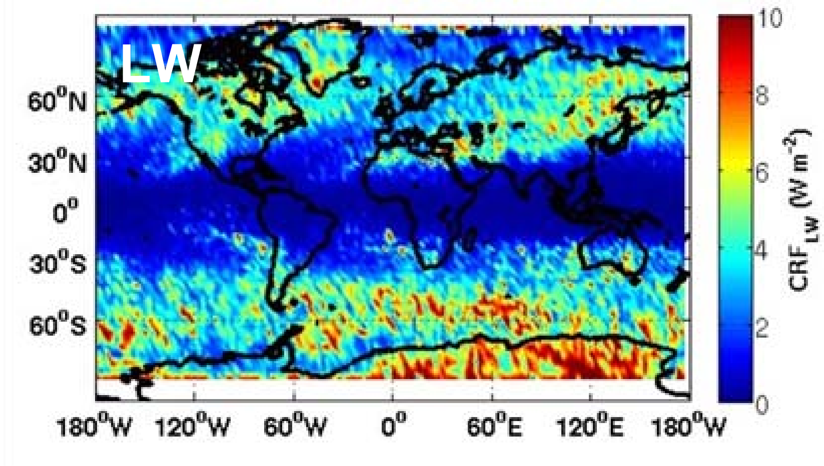


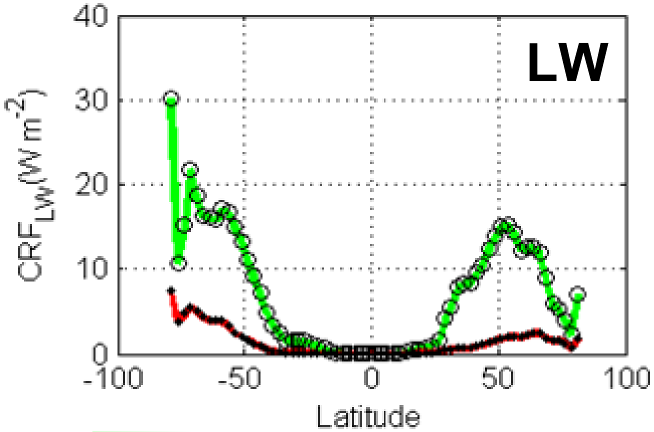
Zonal mean cirrus forcing



⇨ $\overline{CRF}_{SW, all\ cirrus}$ = -22.5 W m$^{-2}$

⇨ $\overline{CRF}_{SW, thin\ cirrus}$ = -2.4 W m$^{-2}$





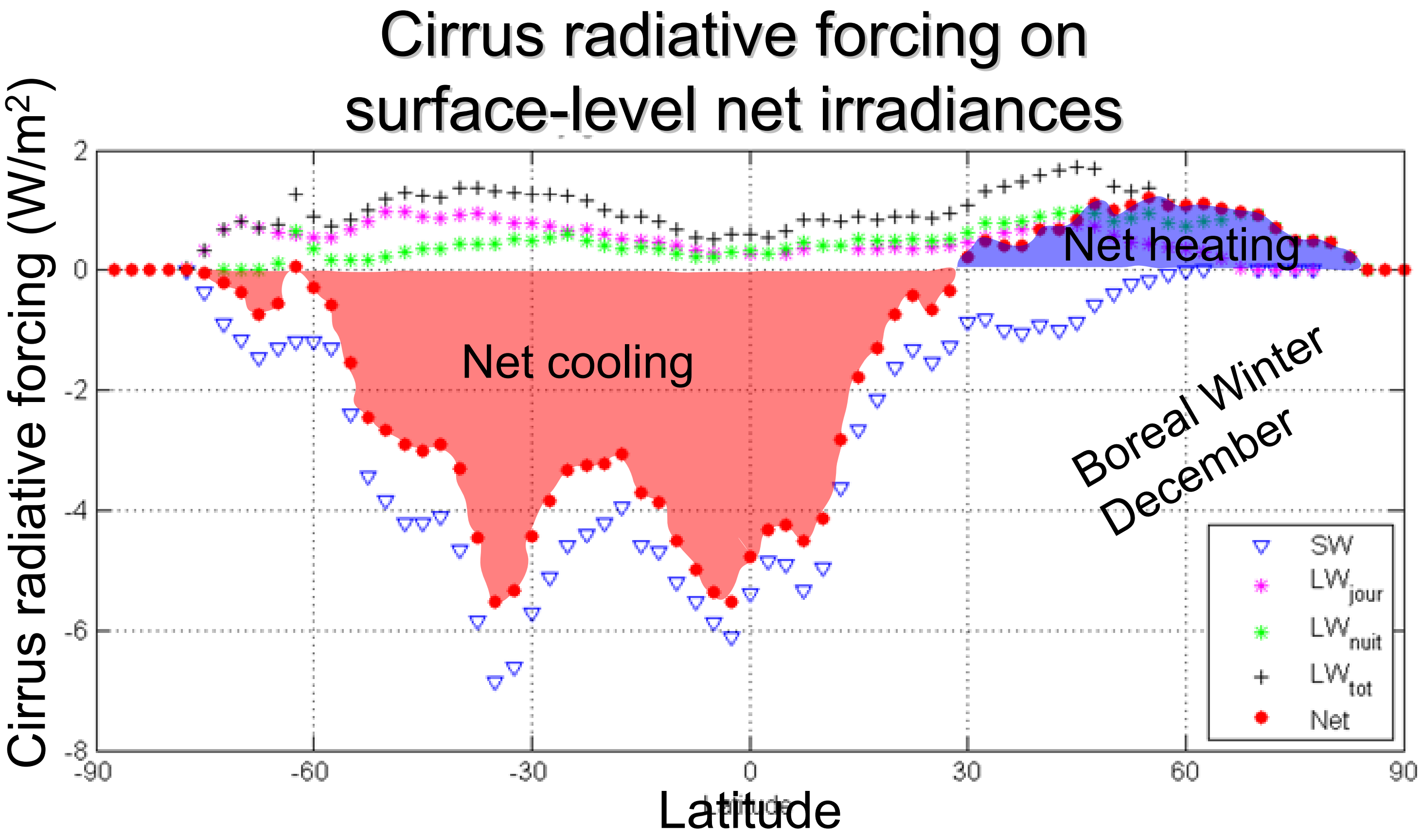
⇨ $\overline{CRF}_{LW, all\ cirrus}$ = +7.2 W m$^{-2}$

⇨ $\overline{CRF}_{LW, thin\ cirrus}$ = +1.4 W m$^{-2}$

*Mean CRF consistent with Chen et al. 2000 (ISCCP + RT)*

# *Cumulative cirrus radiative forcing*

**Account for cirrus properties, aerosol and water vapor, and day/night duration**

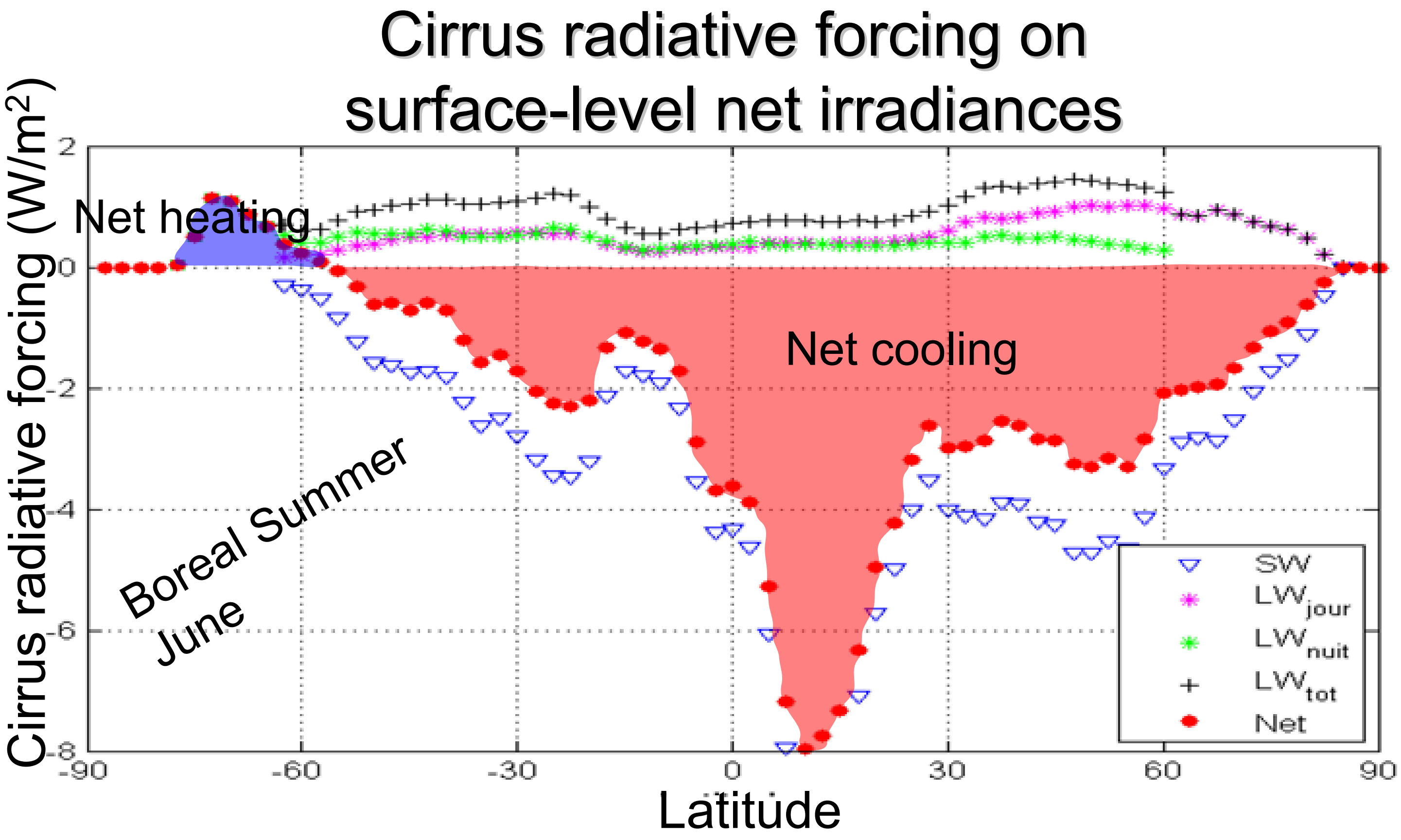


Cirrus radiative forcing on surface-level net irradiances

- ⇨ **Heating effect dominates north of 30° N (+1.5 W m$^{-2}$)**
- ⇨ **Cooling effect maximum at ITCZ and 30° S (-6 W m$^{-2}$)**

# *Cumulative cirrus radiative forcing*

**Account for cirrus properties, aerosol and water vapor, and day/night duration**



- ⇨ **Heating effect dominates south of 45° S (+1.5 W m$^{-2}$)**
- ⇨ **Cooling effect maximum at ITCZ (-8 W m$^{-2}$)**

# Conclusions

Because of their high occurrence, low optical depth cirrus have a measurable effect on the surface energy budget:

- net cooling effect of -3.5W/m2
- strong meridian gradients with net heating at high latitudes
- Mid-Latitude winter: SW cooling of cirrus compensated by LW heating

# Perspectives

- Parametric equations must be validated against other datasets (e.g. ARM mobile facility, CERES/SARB)
- Sensitivity to cloud microphysics should be included
- Role of optically thin cirrus in the context of current global brightening investigations.