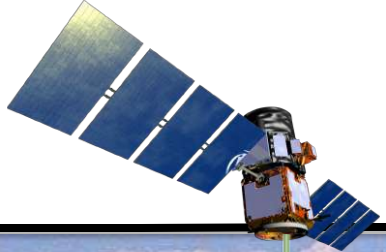
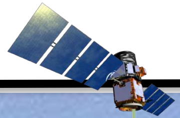




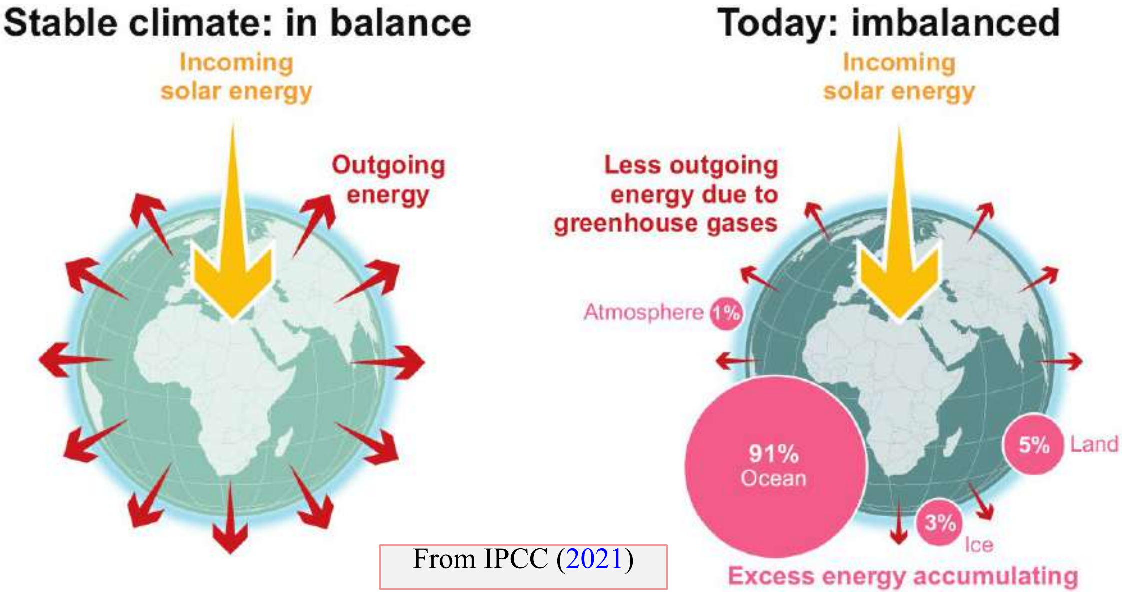
Surface longwave cloud radiative effect derived from space lidar observations: An application to the Arctic

April 21st, 2023: PhD defense

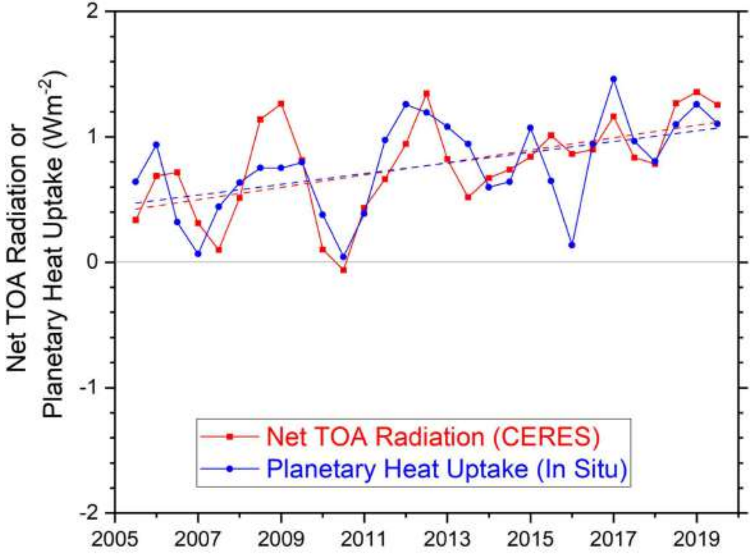
Assia Arouf

Supervisor: Hélène Chepfer

Current Earth energy budget at the top of the atmosphere (TOA)

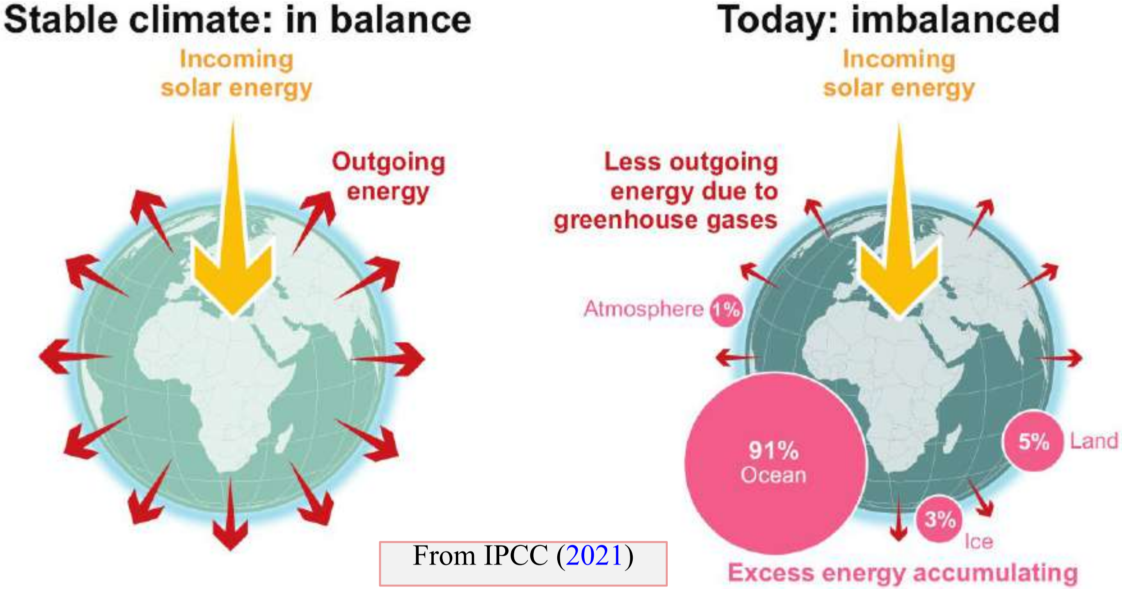


From IPCC (2021)

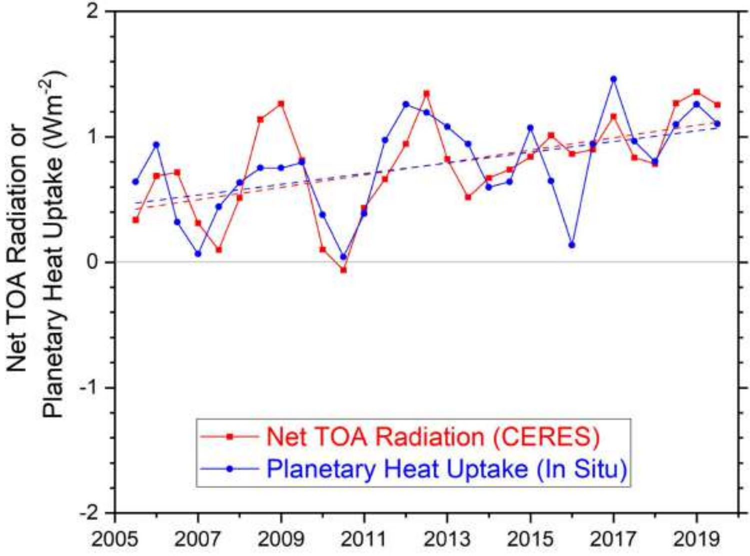


From Loeb et al., (2021)

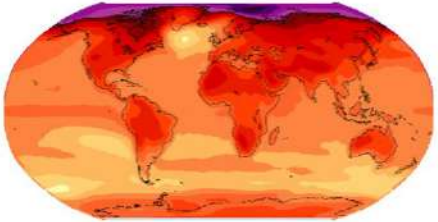
Current Earth energy budget at the top of the atmosphere (TOA)



From IPCC (2021)

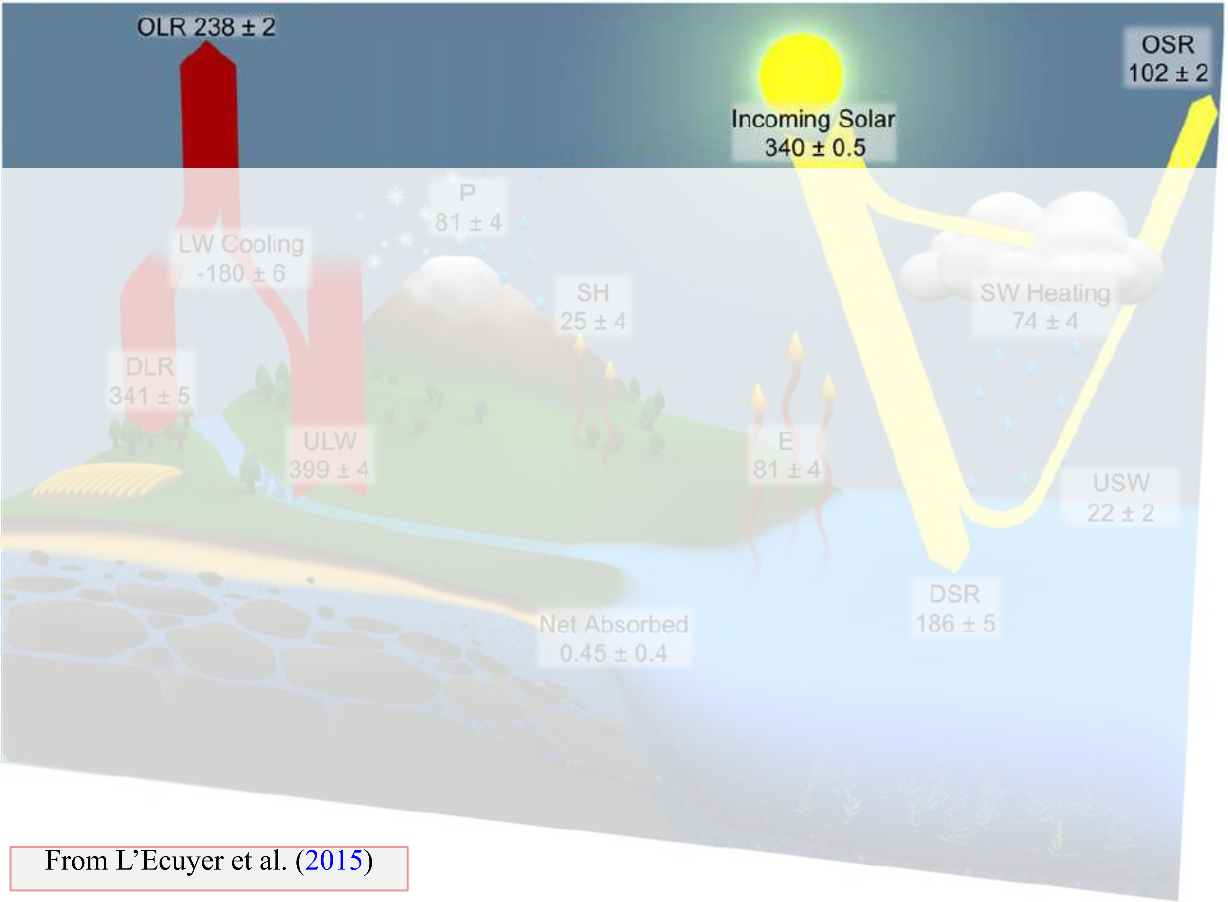


From Loeb et al., (2021)



TS

Component of Earth energy budgets at the TOA

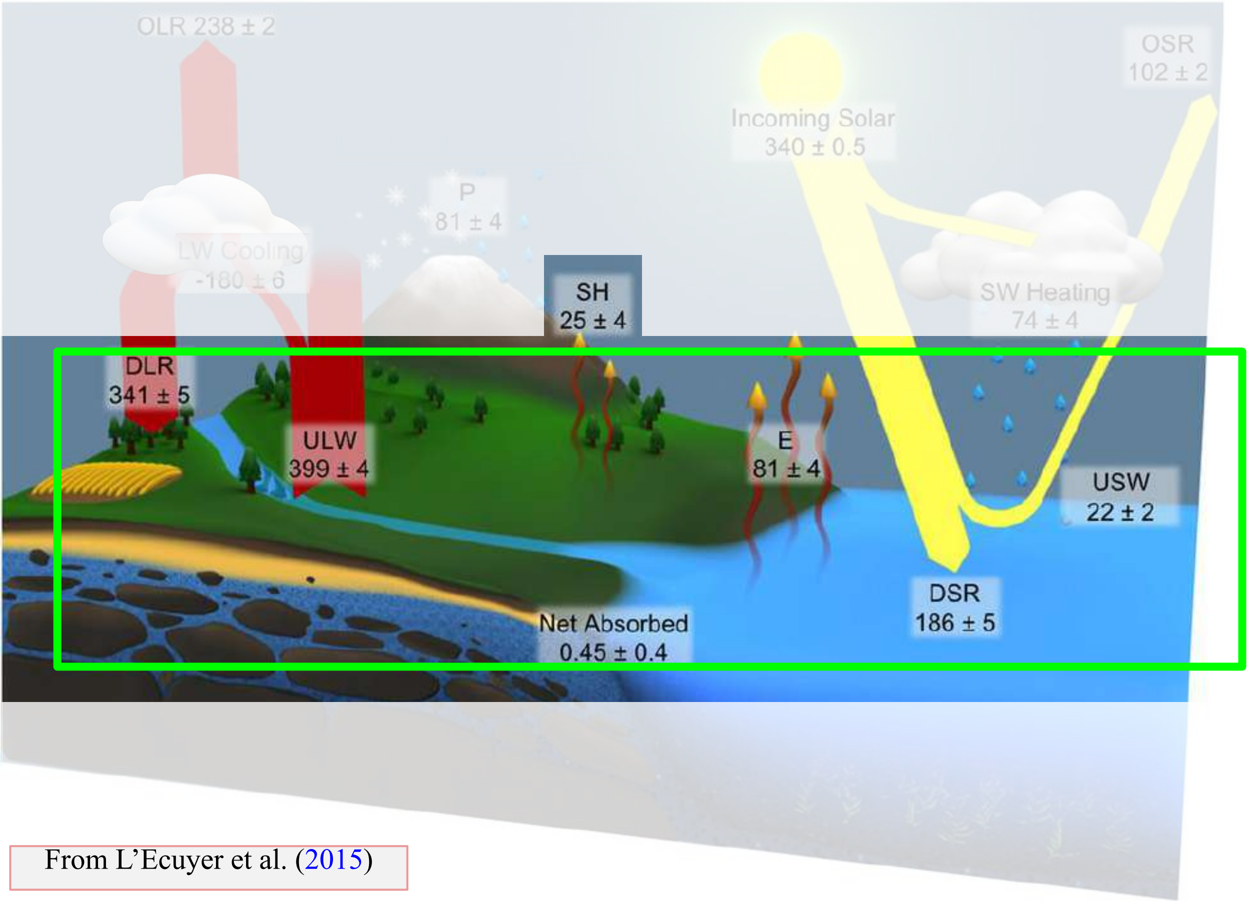


From L'Ecuyer et al. (2015)

❖ ***Radiative only***

(Dines, 1917; London, 1957, Wild et al., 2019)

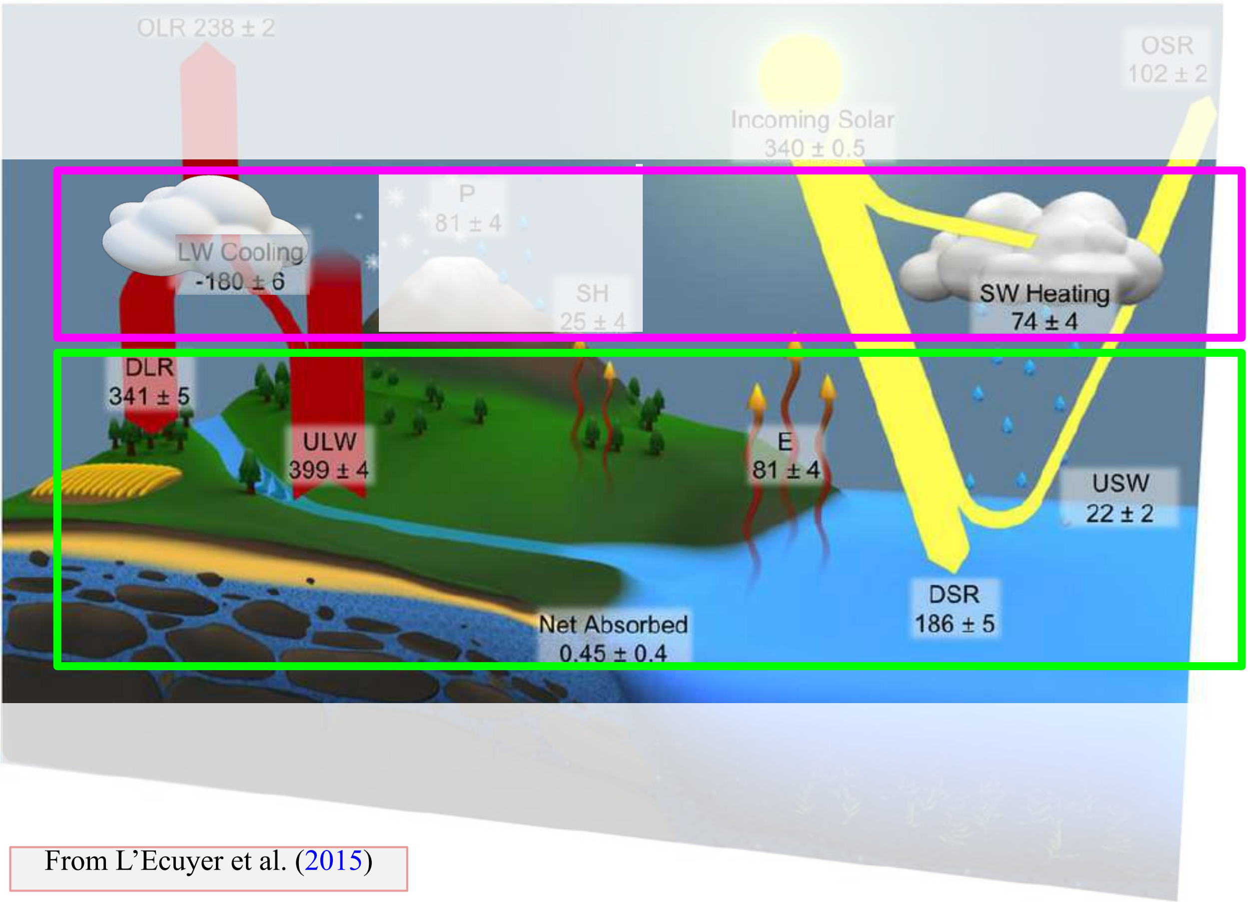
Component of Earth energy budgets at the surface



From L'Ecuyer et al. (2015)

- ***Radiative and convective***
  - *Not well determined on global long time scale (Wild et al., 2019)*

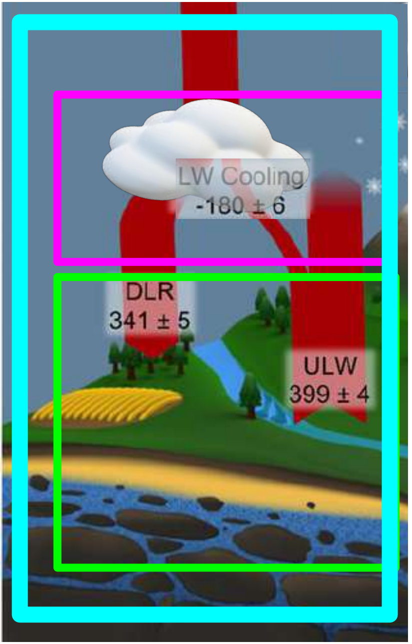
Component of Earth energy budgets: Importance of clouds



From L'Ecuyer et al. (2015)

- Clouds radiatively affect Earth's energy budgets

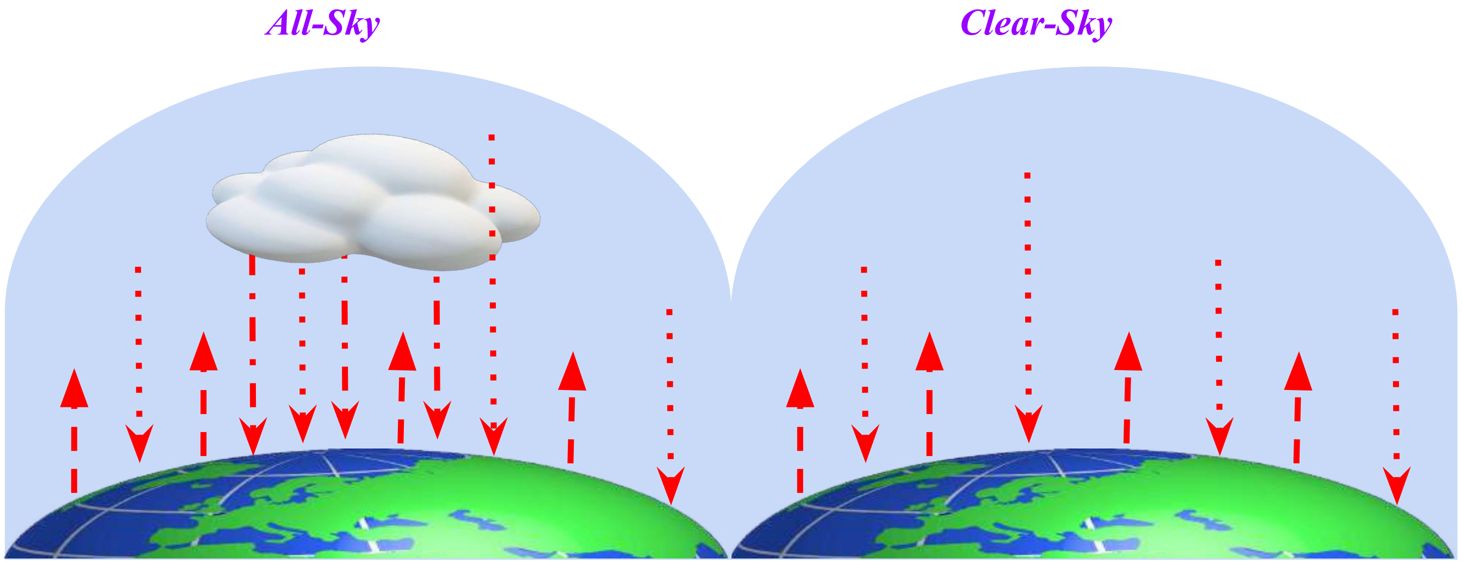
Component of Earth energy budgets at the surface in the longwave (LW)



- ***Clouds radiatively warm the surface in the LW***
  - *May affect Arctic sea ice melt*
  - *Not well determined on global multi-decadal scale*

From L'Ecuyer et al. (2015)

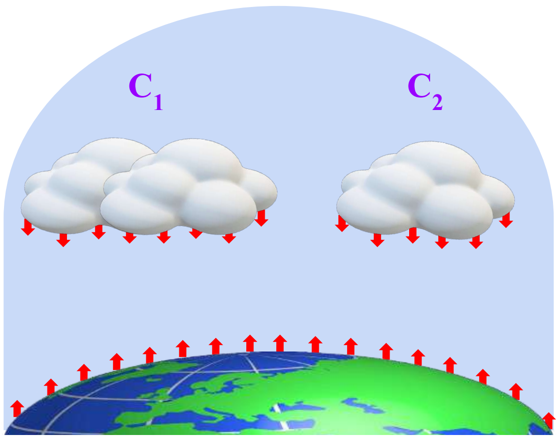
The surface longwave (LW) Clouds Radiative Effects (CRE)



$$CRE_{SFC,\,LW} = (F^{\downarrow} - F^{\uparrow})_{All\text{-}Sky,\,LW} - (F^{\downarrow} - F^{\uparrow})_{Clear\text{-}Sky,\,LW} \quad [W\,m^{-2}]$$

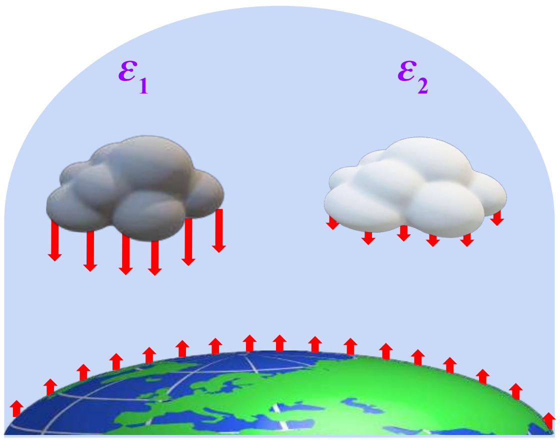
$CRE_{SFC,\,LW} > 0$ when clouds warm the surface.

Cloud properties driving surface LW cloud warming effect



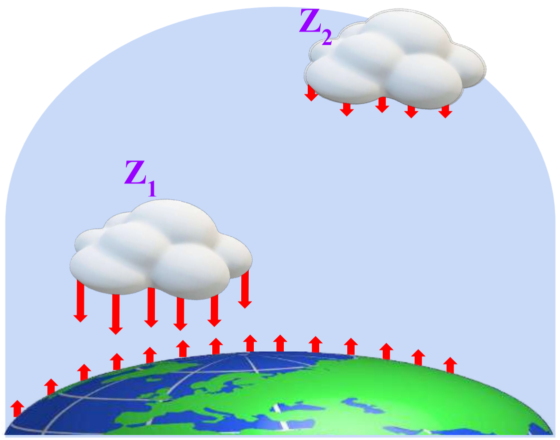
1) Cover (C)

$C_1 > C_2$
Warming 1 > Warming 2



2) Opacity / Emissivity (ε)

$\varepsilon_1 > \varepsilon_2$
Warming 1 > Warming 2

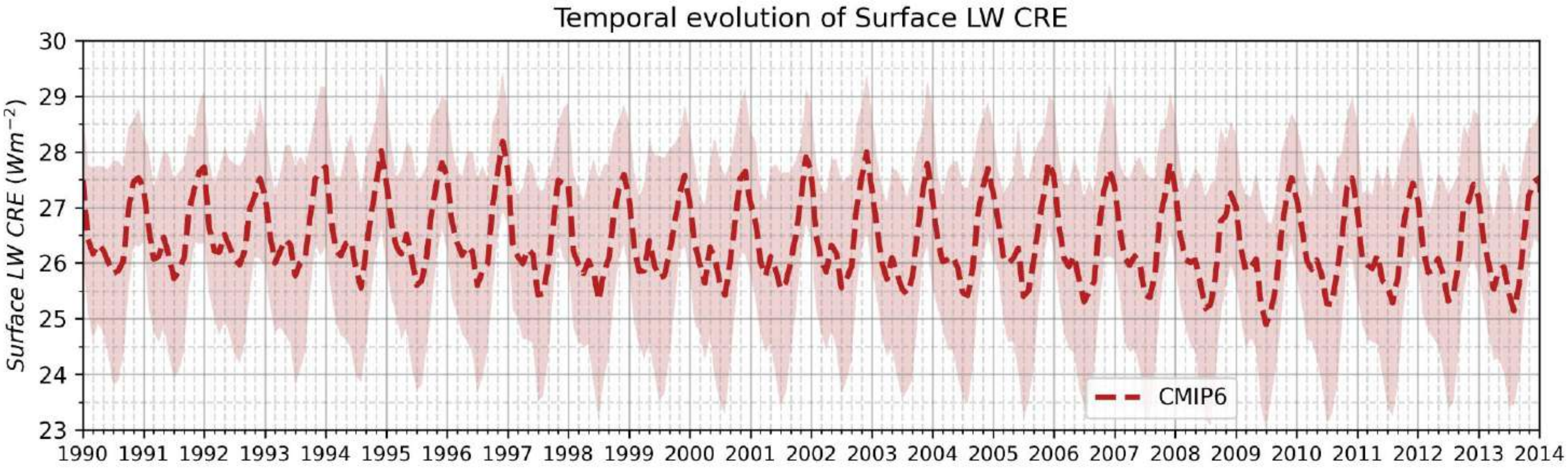


3) Altitude (Z)

$Z_1 < Z_2$
$T_1 > T_2$
Warming 1 > Warming 2

- *Cloud LW warming depend mostly on* ***cloud cover****,* ***cloud emissivity****,* ***cloud altitude****.*

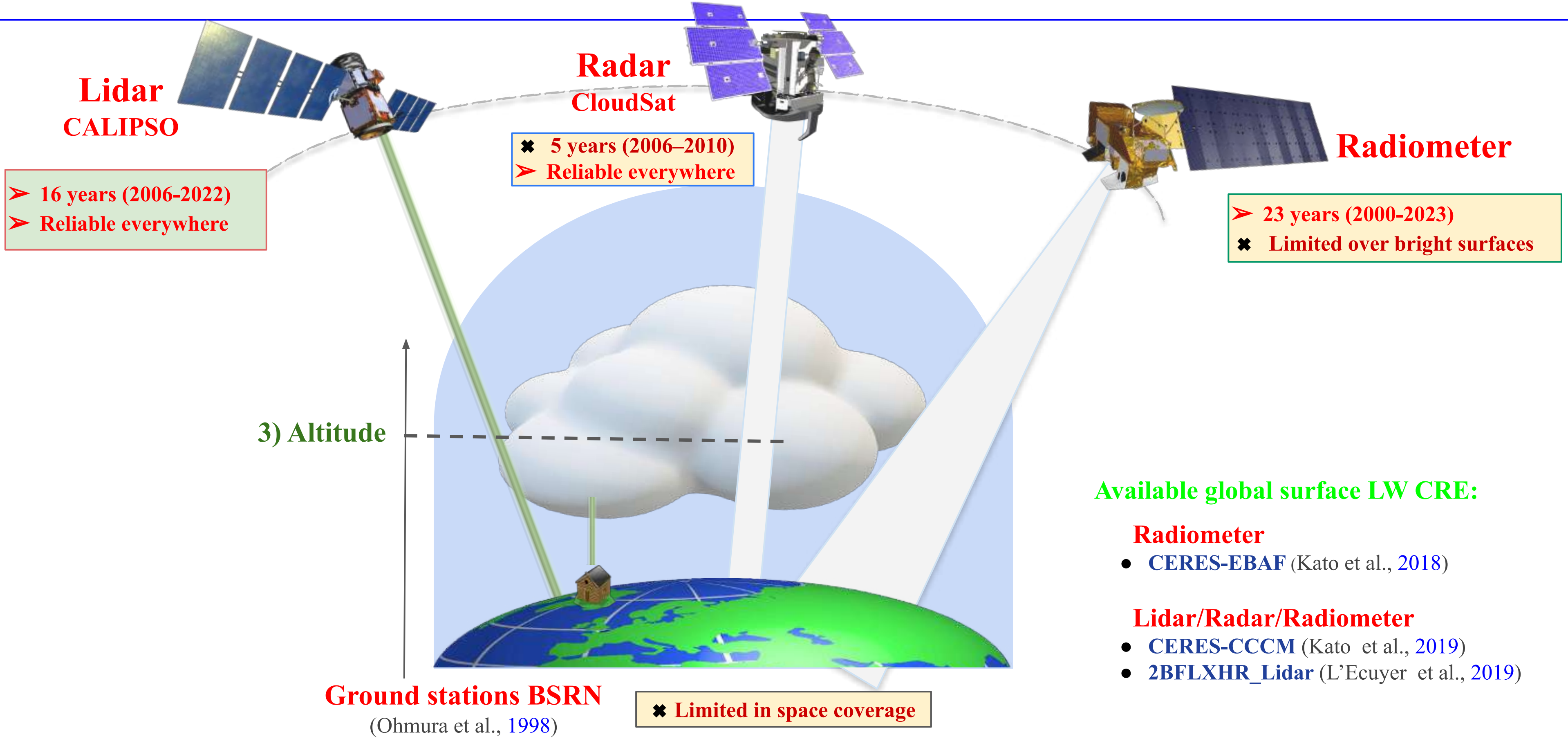
State of knowledge: LW cloud warming effect at the surface in CMIP6 models



Large spread of surface LW cloud warming in CMIP6

Need multidecadal global observation

State of knowledge: LW cloud warming effect at the surface from observations



Available global surface LW CRE:

Radiometer

- **CERES-EBAF** (Kato et al., 2018)

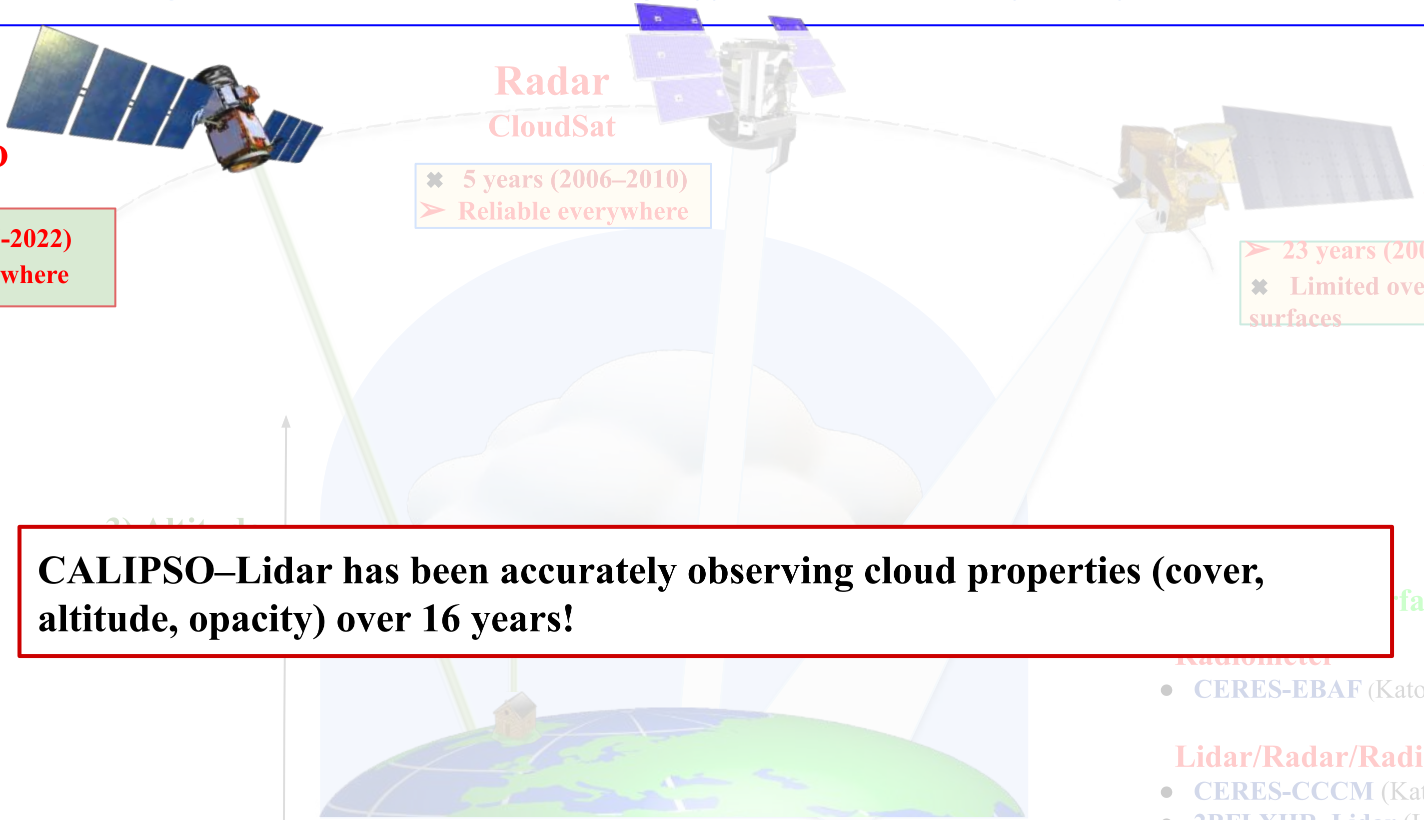
Lidar/Radar/Radiometer

- **CERES-CCCM** (Kato et al., 2019)
- **2BFLXHR_Lidar** (L'Ecuyer et al., 2019)

State of knowledge: LW cloud warming effect at the surface from observations

Lidar
CALIPSO

- ➢ 16 years (2006-2022)
- ➢ Reliable everywhere



Radar
CloudSat

- ✖ 5 years (2006–2010)
- ➢ Reliable everywhere

Radiometer

- ➢ 23 years (2000-2023)
- ✖ Limited over bright surfaces

Radiometer
- CERES-EBAF (Kato et al., 2018)

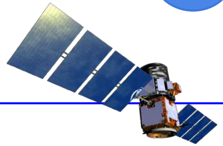
Lidar/Radar/Radiometer
- CERES-CCCM (Kato et al., 2019)
- 2BFLXHR_Lidar (L'Ecuyer et al., 2019)

Ground station BSRN
(Ohmura et al., 1998)

✖ Limited in space coverage

CALIPSO–Lidar has been accurately observing cloud properties (cover, altitude, opacity) over 16 years!

Outline



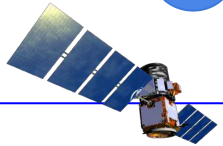
I Surface LW cloud warming over more than a decade from CALIPSO lidar observation

A Retrieval

B Evaluation against independent observations

II Link between surface LW cloud warming and Arctic sea ice loss

Outline



I **Surface LW cloud warming over more than a decade from CALIPSO lidar observation**

A **Retrieval**

Tools

- *Cloud observations from CALIPSO*

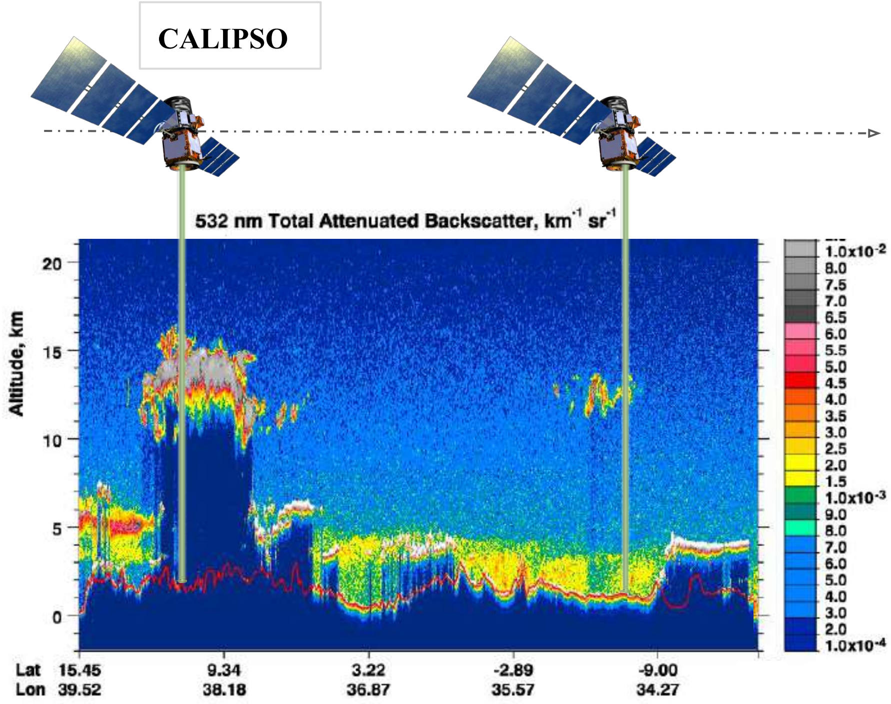
Method

- *Radiative transfer computations*

Results

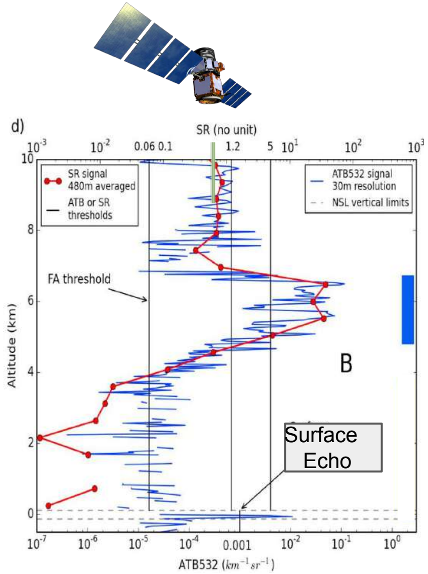
- *Linear parameterizations*
- *Retrieval of surface LWCRE–LIDAR*

Tools: CALIPSO spaceborne Lidar samples the atmosphere vertically



CALIPSO

- **90 m/330 m along orbit track**
- **2006–2022**
- **Surface independent**
- **Thick/Thin**



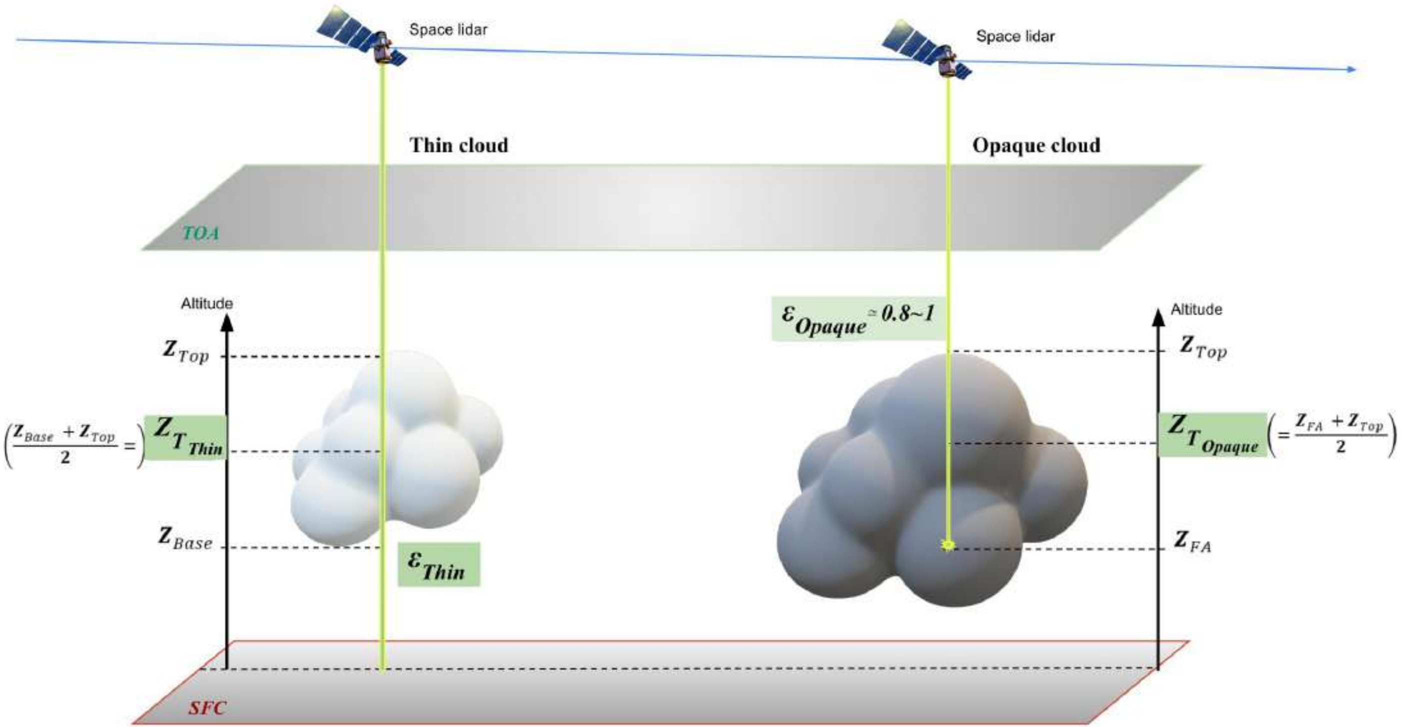
Cloud

$$\varepsilon_{\text{Thin}} = 1 - e^{-\delta\text{-IR}}$$

(Vaillant de Guélis et al., 2017a
Garnier et al., 2015)

From Guzman et al. (2017)

Tools: Cloud properties derived from CALIPSO–Lidar observation along orbit track



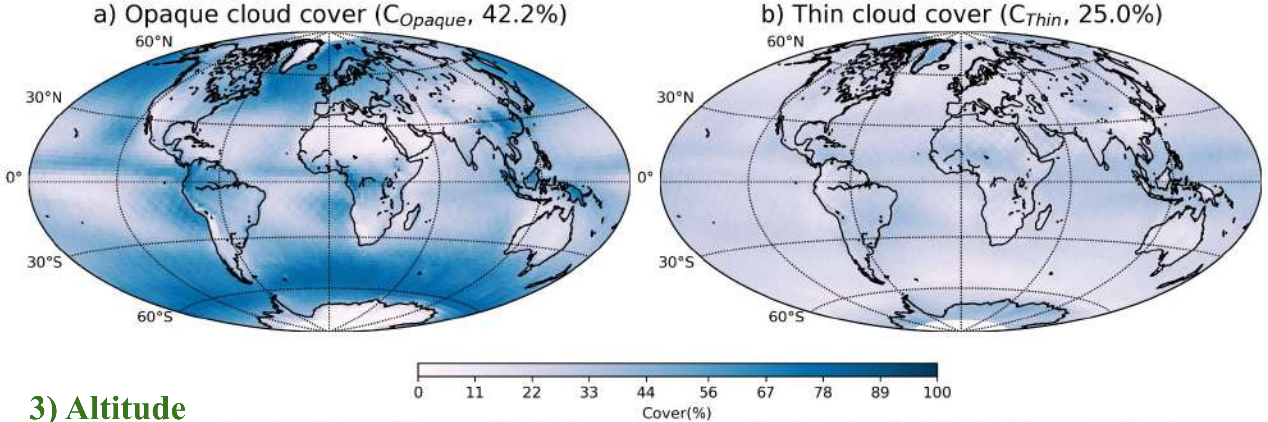
CALIPSO–GOCCP
- **A long orbit track**
- **2008–2020**

CALIPSO–GOCCP
(Chepfer et al., 2010;
Cesana et al., 2012;
Guzman et al., 2017;
Vaillant de Guélis et al., 2017a)

- *From CALIPSO profiles, we can retrieve **cloud cover**, **cloud emissivity**, **cloud altitude**.*

Tools: Maps of cloud properties derived from CALIPSO–Lidar observations

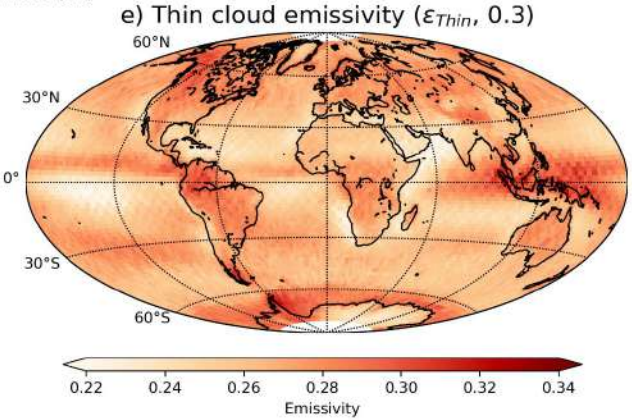
1) Cover



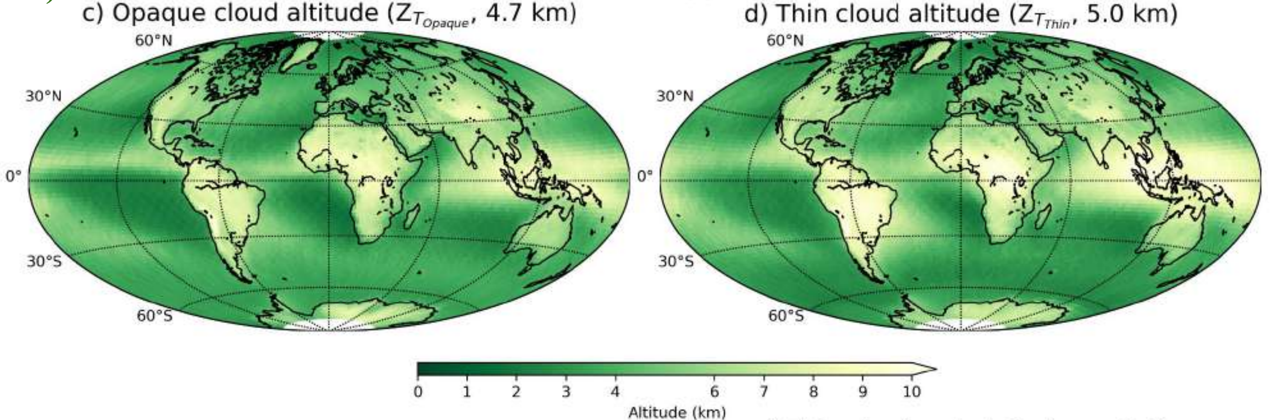
CALIPSO–GOCCP

- **Gridded 2°×2°**
- **2008–2020**

2) Emissivity;

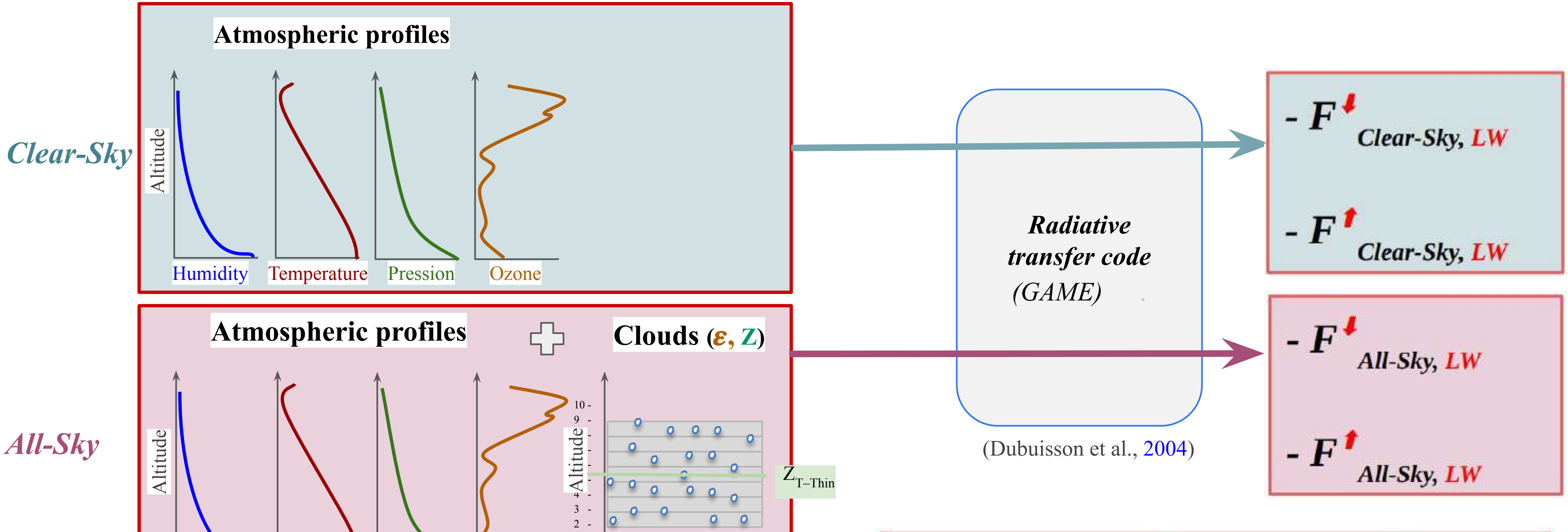


3) Altitude



(Chepfer et al., 2010;
Cesana et al., 2012;
Guzman et al., 2017;
Vaillant de Guélis et al., 2017a)

Method: One radiative transfer computation (1 month and a 2° latitude band)



ERA-I (Dee et al., 2011)

$$CRE_{SFC, LW} = (F^{\downarrow} - F^{\uparrow})_{All-Sky, LW} - (F^{\downarrow} - F^{\uparrow})_{Clear-Sky, LW}$$

*Parametrization between the **surface LW cloud radiative effect** and*

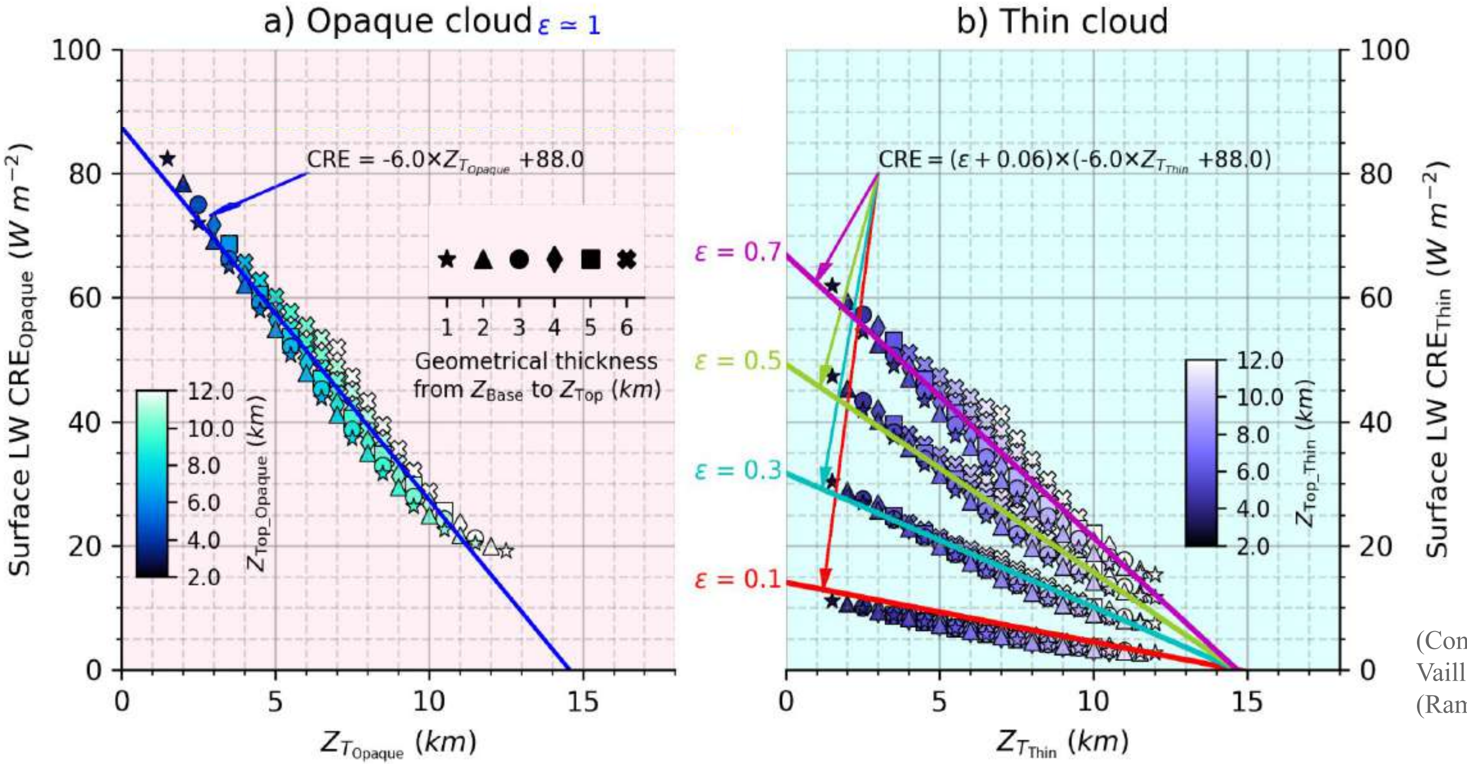
- **Emissivity**
- **Altitude opaque, thin**

Results: Linear relationship between surface LW CRE and cloud properties

One example

Over oceans; January, Lat = 39°N

(Arouf et al., 2022)

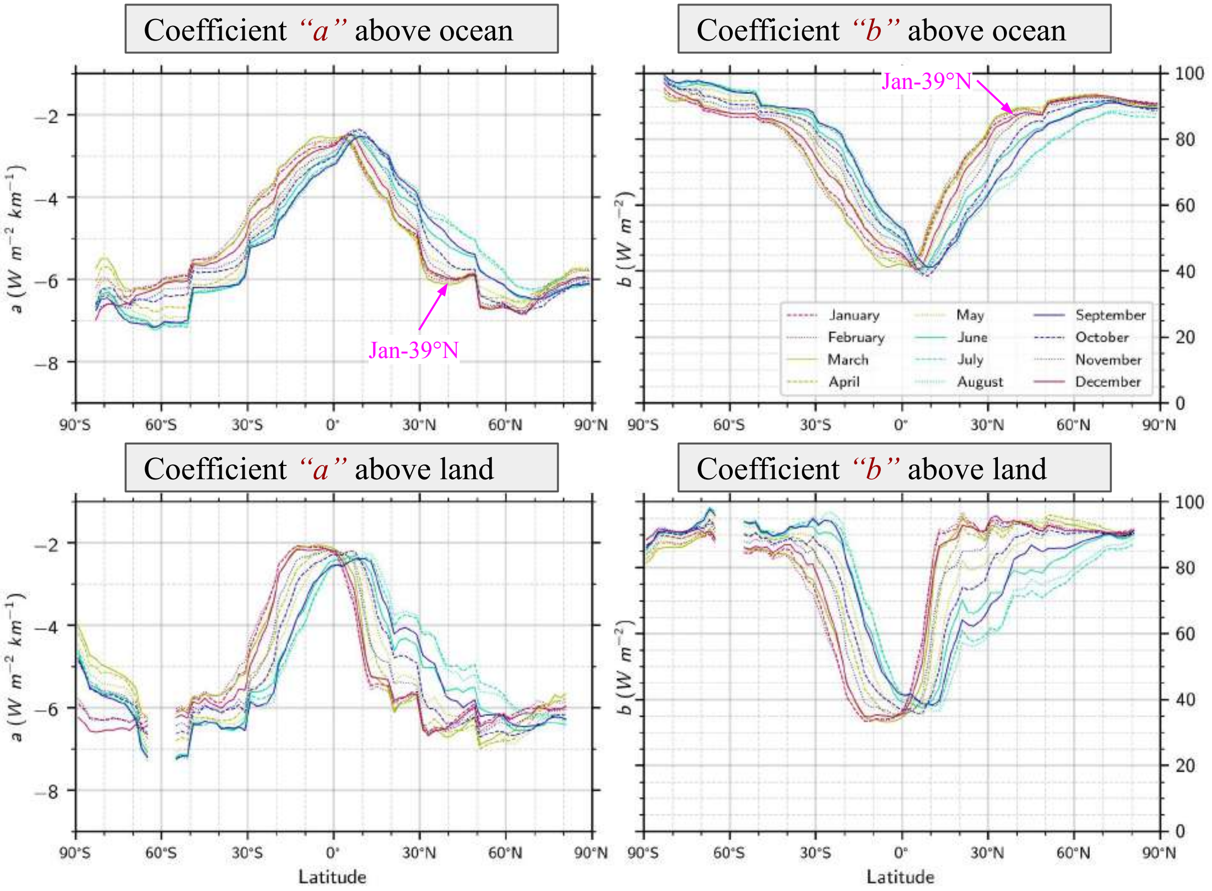


(Consistent with Vaillant de Guélis et al., 2017a) (Ramanathan et al., 1977)

$$\text{LW CRE}_{Opaque} = a(H,T)\times Z_{T\text{-}Opaque} + b(H,T)$$

$$\text{LW CRE}_{Thin} = (\varepsilon_{Thin} + 0.06)\times(a(H,T)\times Z_{T\text{-}Thin} + b(H,T))$$

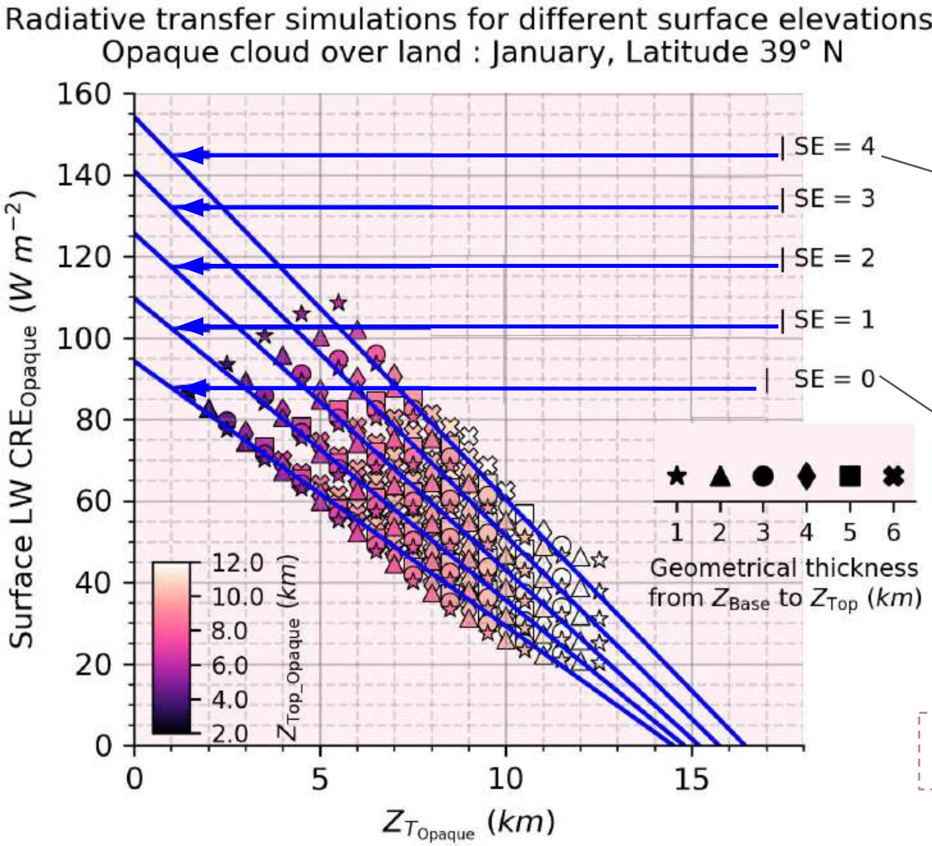
Results: Sensitivity of the coefficients ‘a’ and ‘b’ to humidity and temperature profiles.

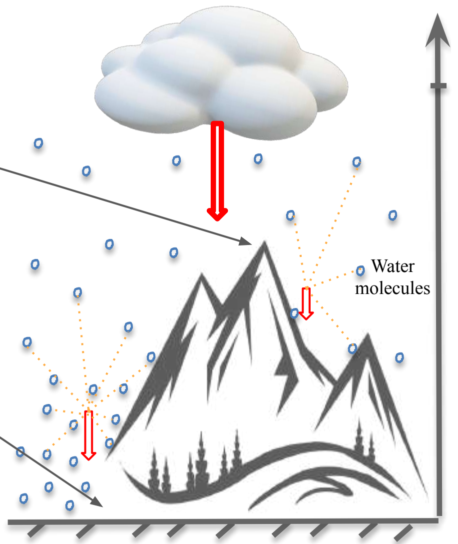


$$\textbf{LW CRE}_{\textbf{Opaque}} = a(\mathrm{H,T}) \times \mathrm{Z}_{\mathrm{T\text{-}Opaque}} + b(\mathrm{H,T})$$

The surface LW cloud radiative effect varies according to the latitude and the month due to variations in humidity and temperature profiles.

Results: Surface LW CRE increase with surface elevation (SE), for a given cloud profile



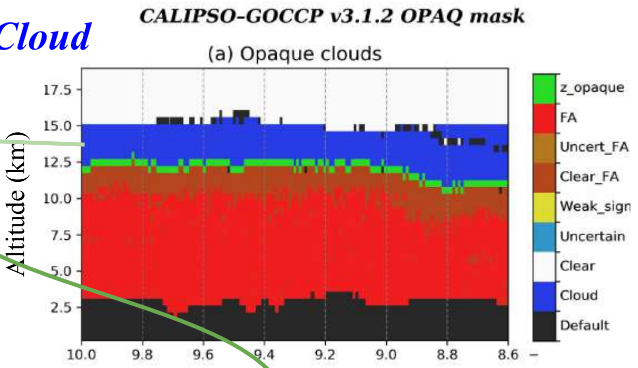


$$\text{LW CRE}_{\text{Opaque}} = a(\text{H,T,SE}) \times Z_{\text{T-Opaque}} + b(\text{H,T,SE})$$

Results: New retrieval of surface LWCRE-LIDAR from CALIPSO (2008–2020)

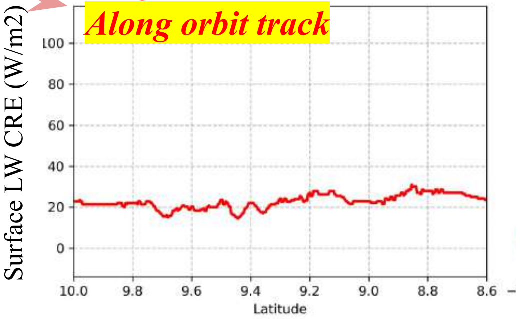
Cloud

$Z_{T\text{–}Opaque}$



$$\text{LW CRE}_{Opaque} = a_{(H,T,SE)} \times Z_{T\text{-}Opaque} + b_{(H,T,SE)}$$

Surface LWCRE–LIDAR
Along orbit track

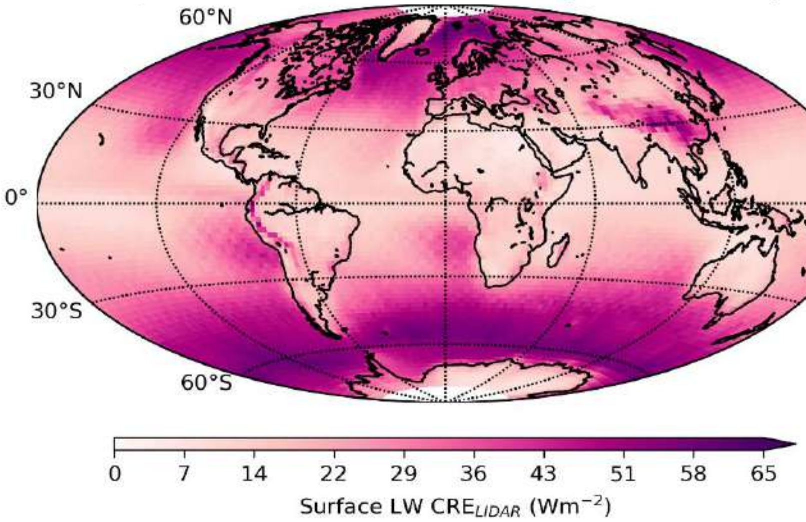


Gridded cloud properties (C, Z, ε)

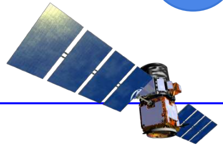
$$\text{LW CRE}_{Opaque} = C_{Opaque} \times \left(a_{(H,T,SE)} \times Z_{T\text{-}Opaque} + b_{(H,T,SE)}\right)$$

Surface LWCRE–LIDAR Gridded 2°×2°

$(27.0\ Wm^{-2})$



Outline



I **Surface LW cloud warming over more than a decade from CALIPSO lidar observation**

A **Retrieval**

B **Evaluation against independent observations**

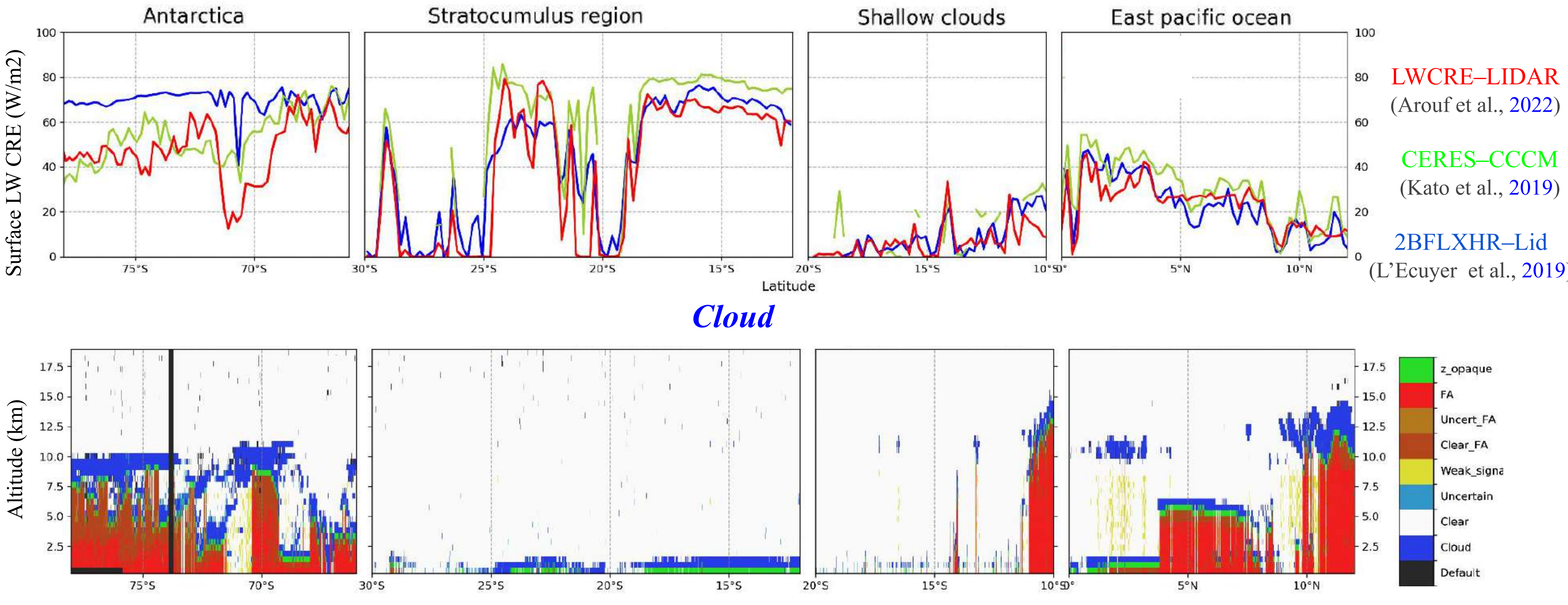
Comparison of LWCRE–LIDAR with other satellite products
- *along orbit tracks*
- *to instantaneous collocated data*
- *to gridded products*

Comparison of LWCRE satellite products with ground stations

Results: Comparison of satellite retrieval along orbit track

Along orbit segments

Surface LW CRE



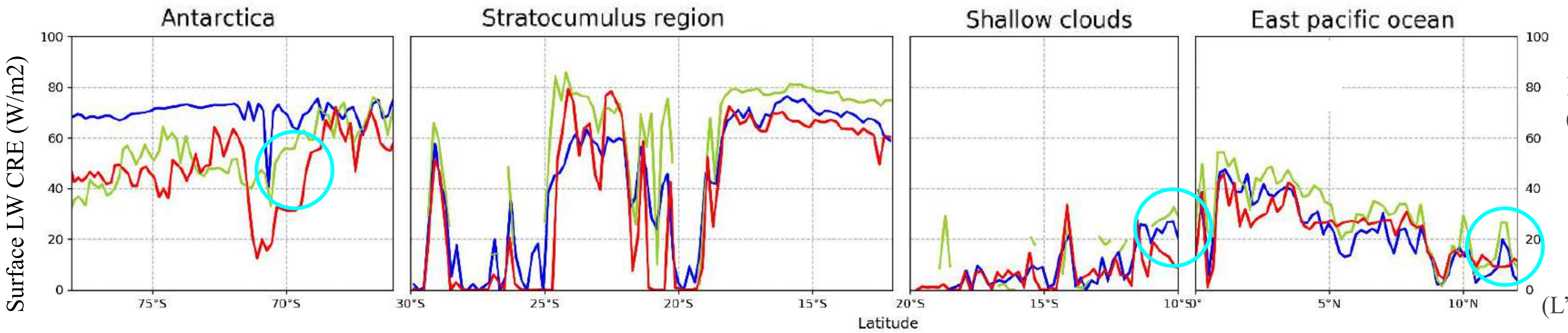
(Guzman et al., 2017)

Surface LW CREs agree well except in deep convective clouds (up to 15 W m^{-2})

Results: Comparison of satellite retrieval along orbit track

Along orbit segments

Surface LW CRE

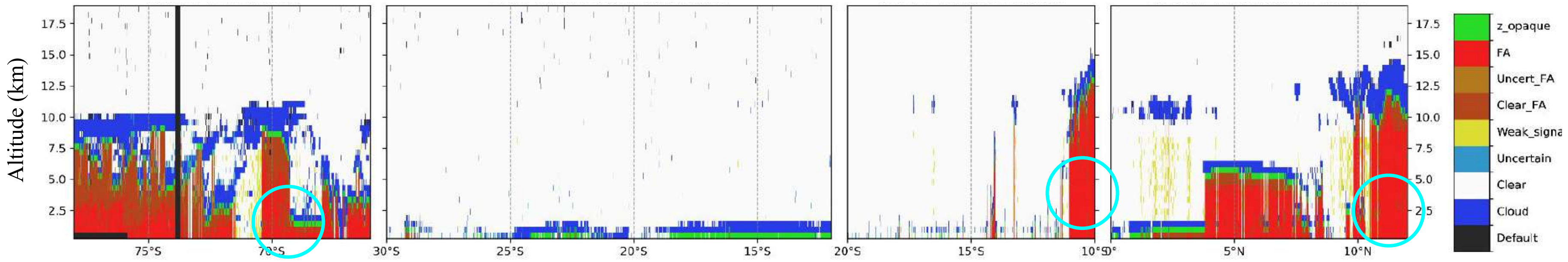


LWCRE–LIDAR (Arouf et al., 2022)

CERES–CCCM (Kato et al., 2019)

2BFLXHR–Lid (L'Ecuyer et al., 2019)

Cloud



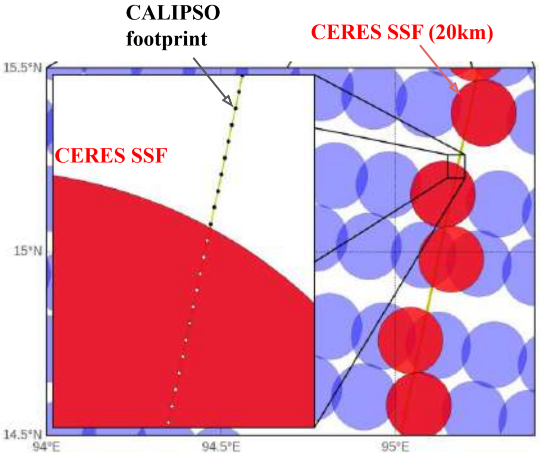
(Guzman et al., 2017)

Surface LW CREs agree well except in deep convective clouds (up to 15 W m^{-2})

Results: Comparison of instantaneous collocated data along orbit track

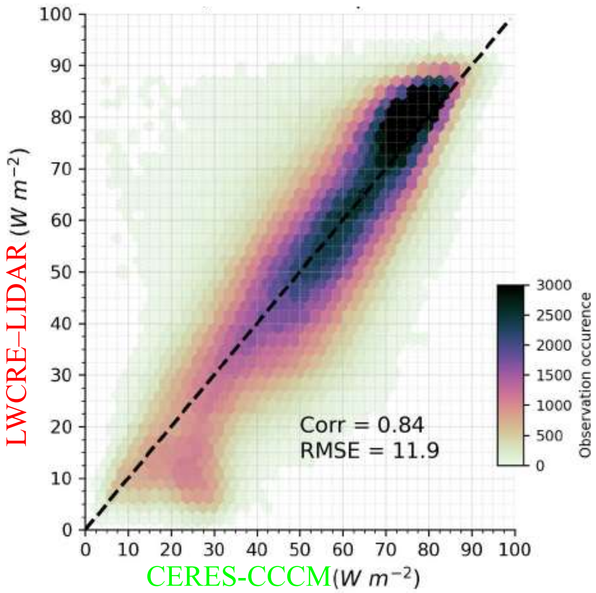
Collocated footprints

- **Statistical comparison (2008 over Oceans)**



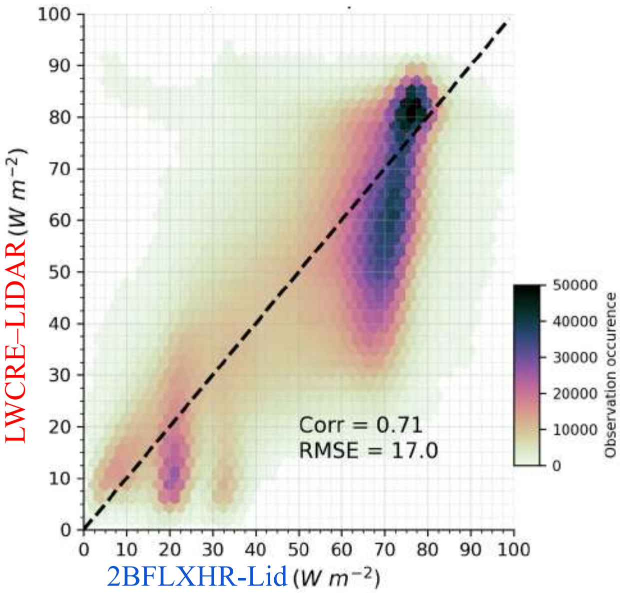
(Vaillant de Guélis, 2017)

LWCRE–LIDAR Vs CERES-CCCM



(Kato et al., 2019)

LWCRE–LIDAR Vs 2BFLXHR-Lid



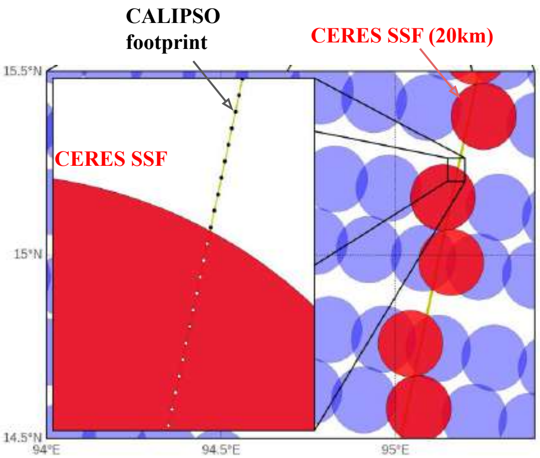
(L'Ecuyer et al., 2019)

- *Correlations > 0.7 between the datasets*

Results: Comparison of instantaneous collocated data along orbit track

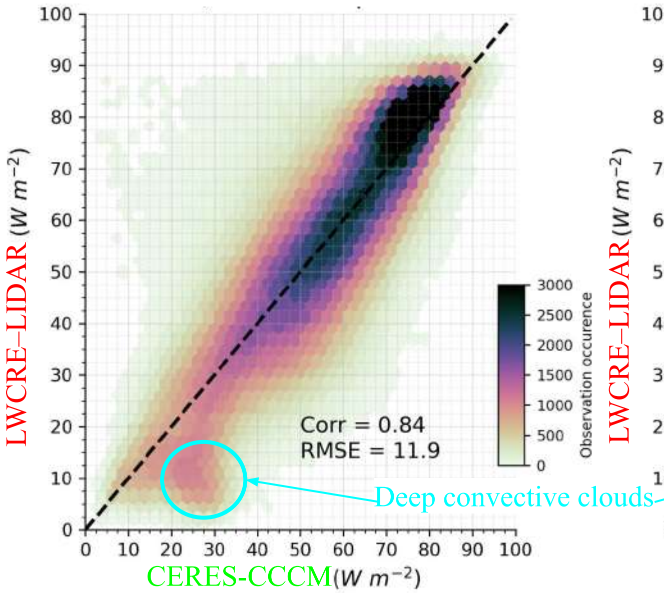
Collocated footprints

- **Statistical comparison (2008 over Oceans)**



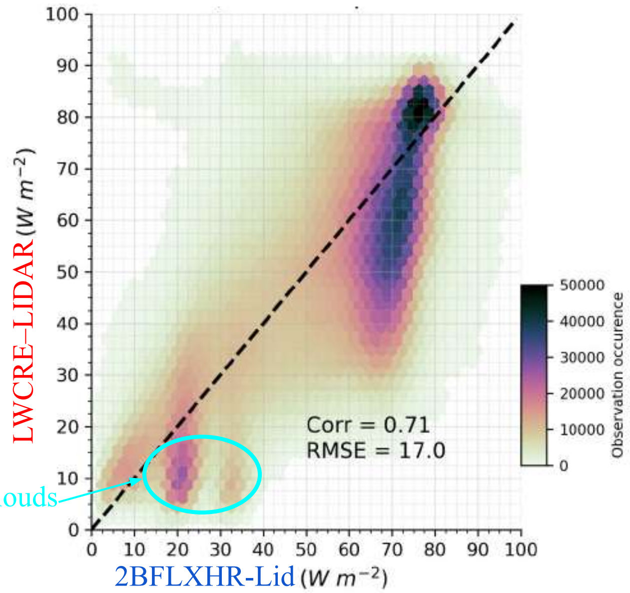
(Vaillant de Guélis, 2017)

LWCRE–LIDAR Vs CERES-CCCM



(Kato et al., 2019)

LWCRE–LIDAR Vs 2BFLXHR-Lid



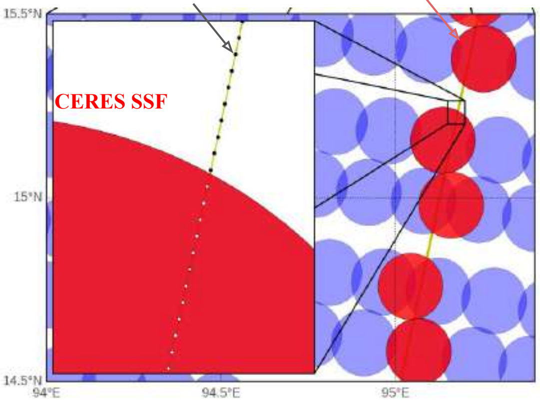
(L'Ecuyer et al., 2019)

- *Correlations > 0.7 between the datasets*
- *7% of CALIPSO profiles have differences reaching 15 W m^{-2}*

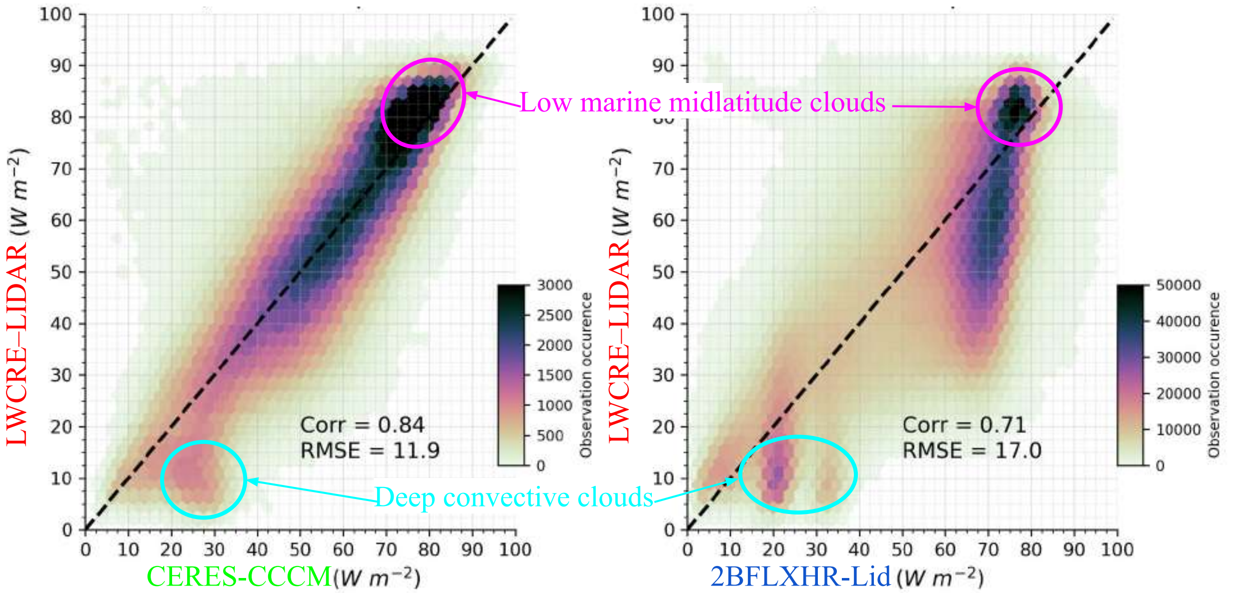
Results: Comparison of instantaneous collocated data along orbit track

Collocated footprints

- **Statistical comparison (2008 over Oceans)**



(Vaillant de Guélis, 2017)



(Kato et al., 2019)

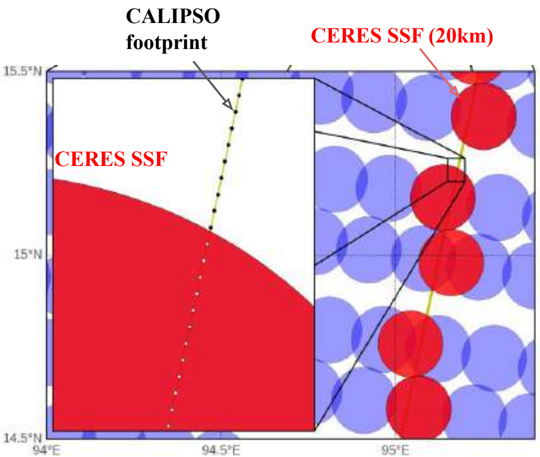
(L'Ecuyer et al., 2019)

- *Correlations > 0.7 between the datasets*
- *7% of CALIPSO profiles have differences reaching 15 W m^{-2}*

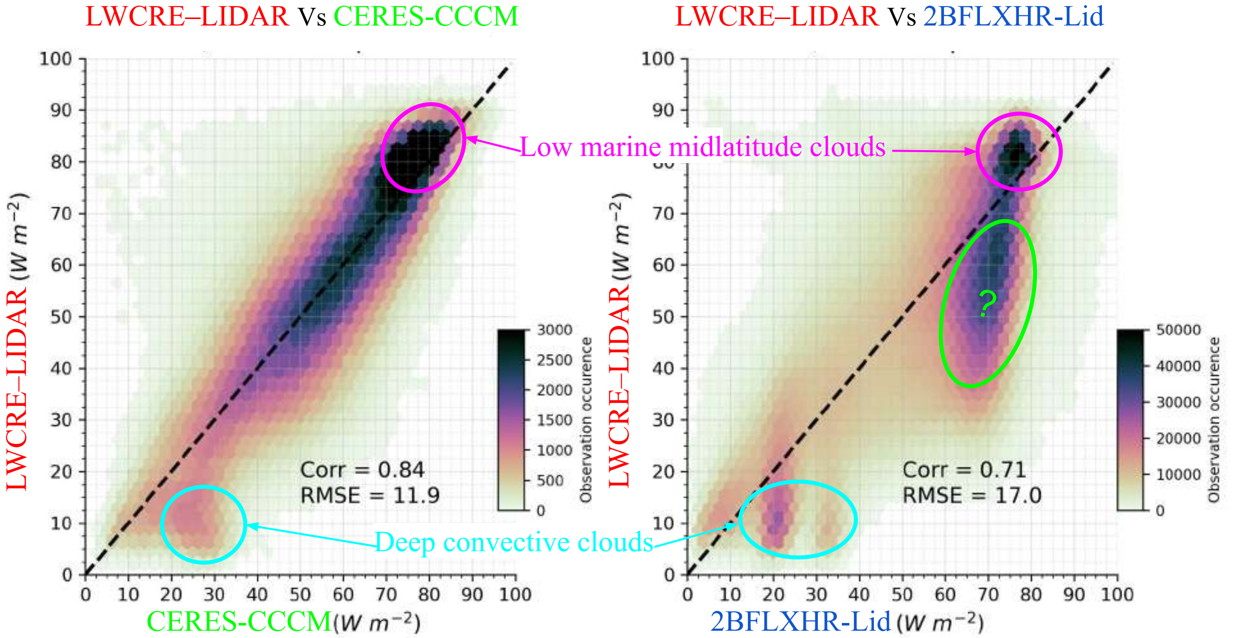
Results: Comparison of instantaneous collocated data along orbit track

- **Statistical comparison (2008 over Oceans)**

Collocated footprints



(Vaillant de Guélis, 2017)



(Kato et al., 2019) (L'Ecuyer et al., 2019)

- *Correlations > 0.7 between the datasets*
- *7% of CALIPSO profiles have differences reaching 15 W m^{-2}*

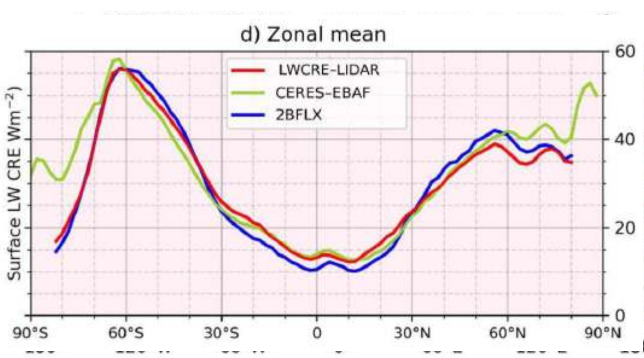
Results: Comparison of global maps (2°×2°, 2008–2010)

Gridded satellites

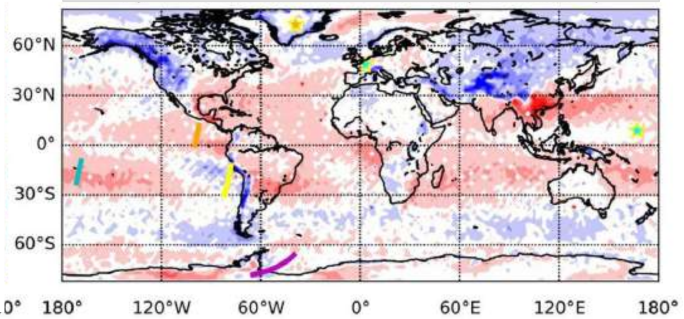
LWCRE–LIDAR
(Arouf et al., 2022)

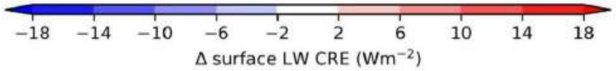
2BFLXHR-Lid
(L'Ecuyer et al., 2019)

CERES-EBAF
(Kato et al., 2018)

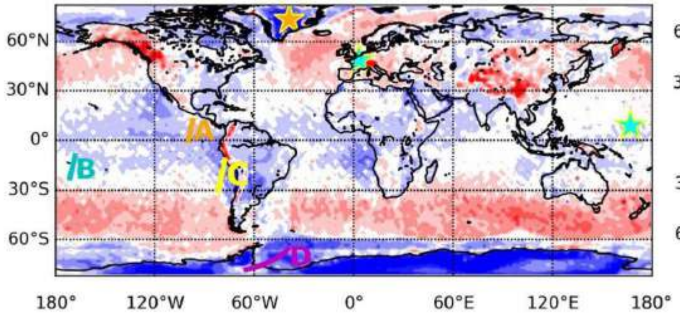


LWCRE–LIDAR - 2BFLXHR–Lid (+0.7 W m^{-2})

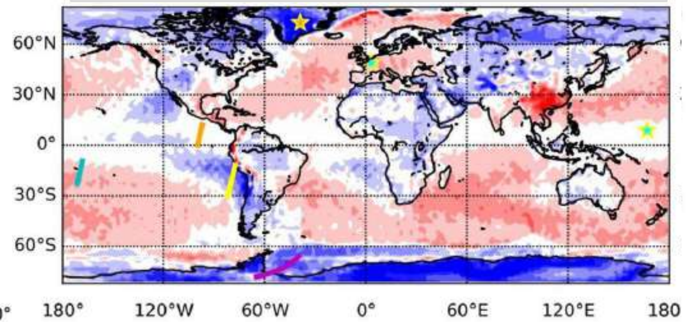




2BFLXHR–Lid - CERES–EBAF (-0.7 W m^{-2})



LWCRE–LIDAR - CERES–EBAF (0.0 W m^{-2})



MODIS over detect clouds in polar regions (GEWEX CA, 2012)

Better agreement between CRE Lidar and CRE Radar/Lidar/Radiometer than with CRE Radiometer especially over polar regions

Results: The surface LWCRE–LIDAR is the closest to ground based observations

Ground stations

Polaires

(Shupe et al., 2013)

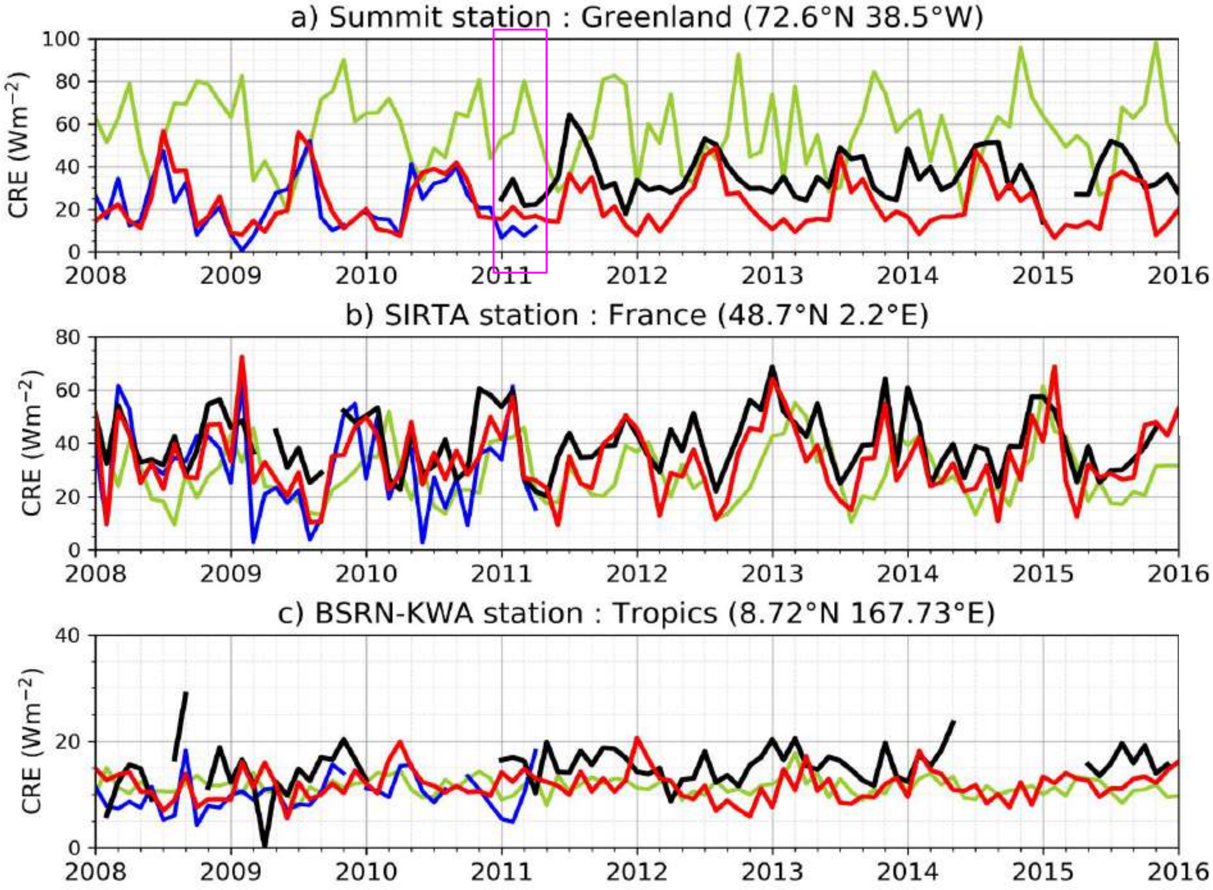
(Lacour et al., 2017)

Mid-latitudes

(Chiriaco et al., 2018)

Tropiques

(Roesch et al., 2011)



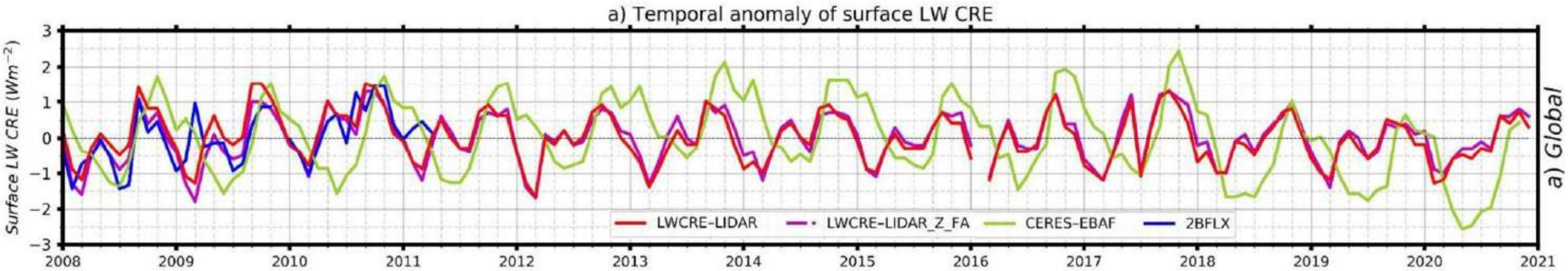
Ground station = 25.7 Wm^{-2}
LWCRE–LIDAR = 17.2 Wm^{-2}
CERES–EBAF = 62.3 Wm^{-2}
2BFLXHR–Lid = 9.3 Wm^{-2}

Ground station = 40.3 Wm^{-2}
LWCRE–LIDAR = 34.6 Wm^{-2}
CERES–EBAF = 28.2 Wm^{-2}
2BFLXHR–Lid = 30.9 Wm^{-2}

Ground station = 14.0 Wm^{-2}
LWCRE–LIDAR = 11.7 Wm^{-2}
CERES–EBAF = 11.3 Wm^{-2}
2BFLXHR–Lid = 9.9 Wm^{-2}

Results: 13 years global interannual variations of the surface LWCRE–LIDAR

Global scale (satellites)



2BFLXHR–Lid :
- ➢ Active remote sensing
- ✖ *5 years of observations*

(L'Ecuyer et al., 2019)

CERES–EBAF :
- ✖ *Passive remote sensing*
- ➢ 20 years of observations

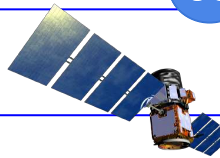
(Kato et al., 2018)

LWCRE–LIDAR :
- ➢ Active remote sensing
- ➢ 13 years of observations

(Arouf et al., 2022)

- *CRE Lidar and CRE Radar/Lidar/Radiometer agree well over 3 years and CRE Lidar last for 13 years.*
- *CRE Radiometer is shifted by 2 to 3 months compared to CRE Lidar and CRE Radar/Lidar/Radiometer.*

First conclusions



- New retrieval of surface LW CRE from CALIPSO between 2008-2020 on global scale.
- Max local differences of 13 W m^{-2} in the gridded product over surfaces ≥ 3 km.
- Max local differences of 10 to 15 W m^{-2} in the orbit product in deep convective clouds but occur only 7% of the time.
- 13 years of surface LWCRE–LIDAR reliable over polar regions.

The surface longwave cloud radiative effect derived from space lidar observations

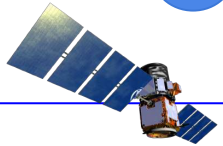
Atmospheric Measurement Techniques
Open Access
EGU

Assia Arouf[1], Hélène Chepfer[1], Thibault Vaillant de Guélis[2,3], Marjolaine Chiriaco[4], Matthew D. Shupe[5,6], Rodrigo Guzman[1], Artem Feofilov[1], Patrick Raberanto[7], Tristan S. L'Ecuyer[8], Seiji Kato[3], and Michael R. Gallagher[5,6]

https://doi.org/10.5194/amt-15-3893-2022

Received: 20 November 2021 – Discussion started: 23 December 2021
Revised: 5 April 2022 – Accepted: 30 May 2022 – Published: 1 July 2022

Outline



I **Surface LW cloud warming over more than a decade from CALIPSO lidar observation**

II **Link between surface LW cloud warming and Arctic sea ice loss**

Context

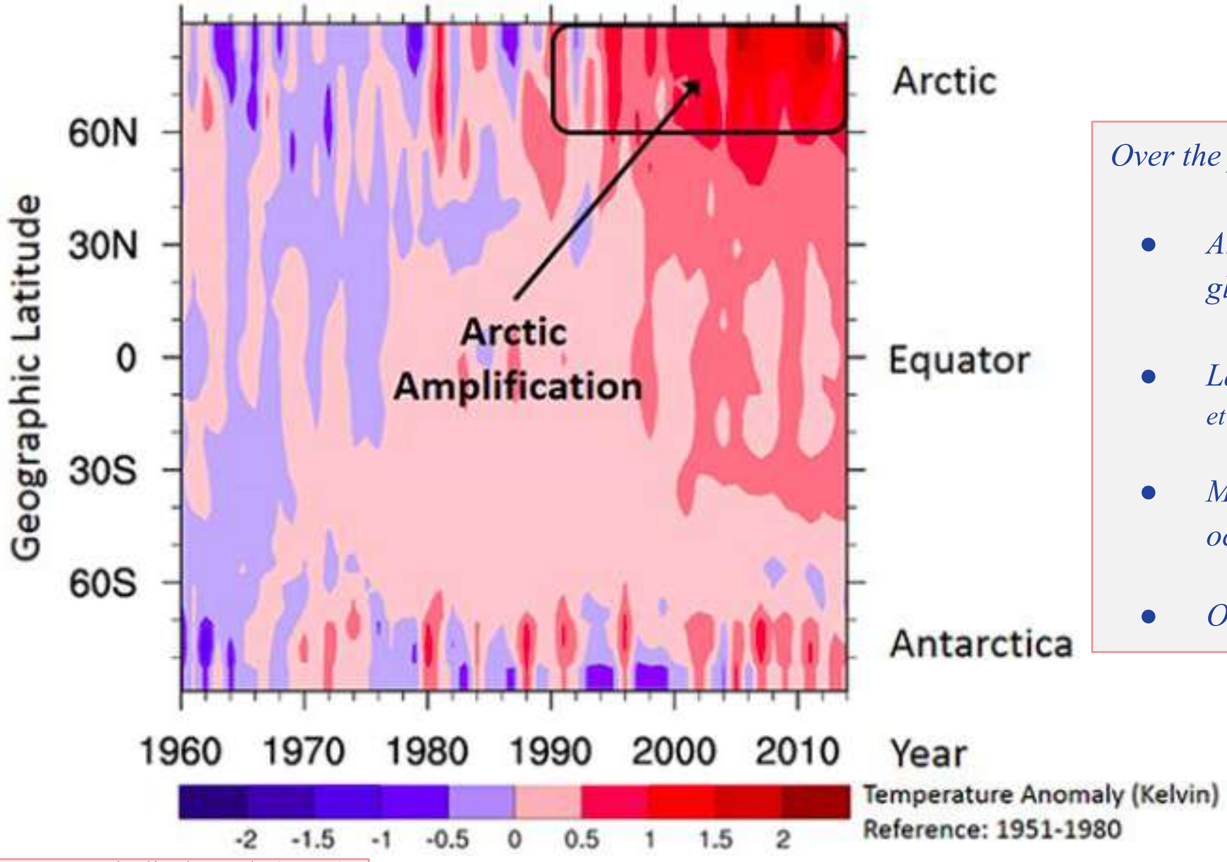
Method

- *Isolate a region where Arctic sea ice varies*

Results

- *Distribution of surface cloud warming within this region*
- *Split surface cloud warming into over open water and over sea ice*

Context: Fast surface temperature increase in the Arctic

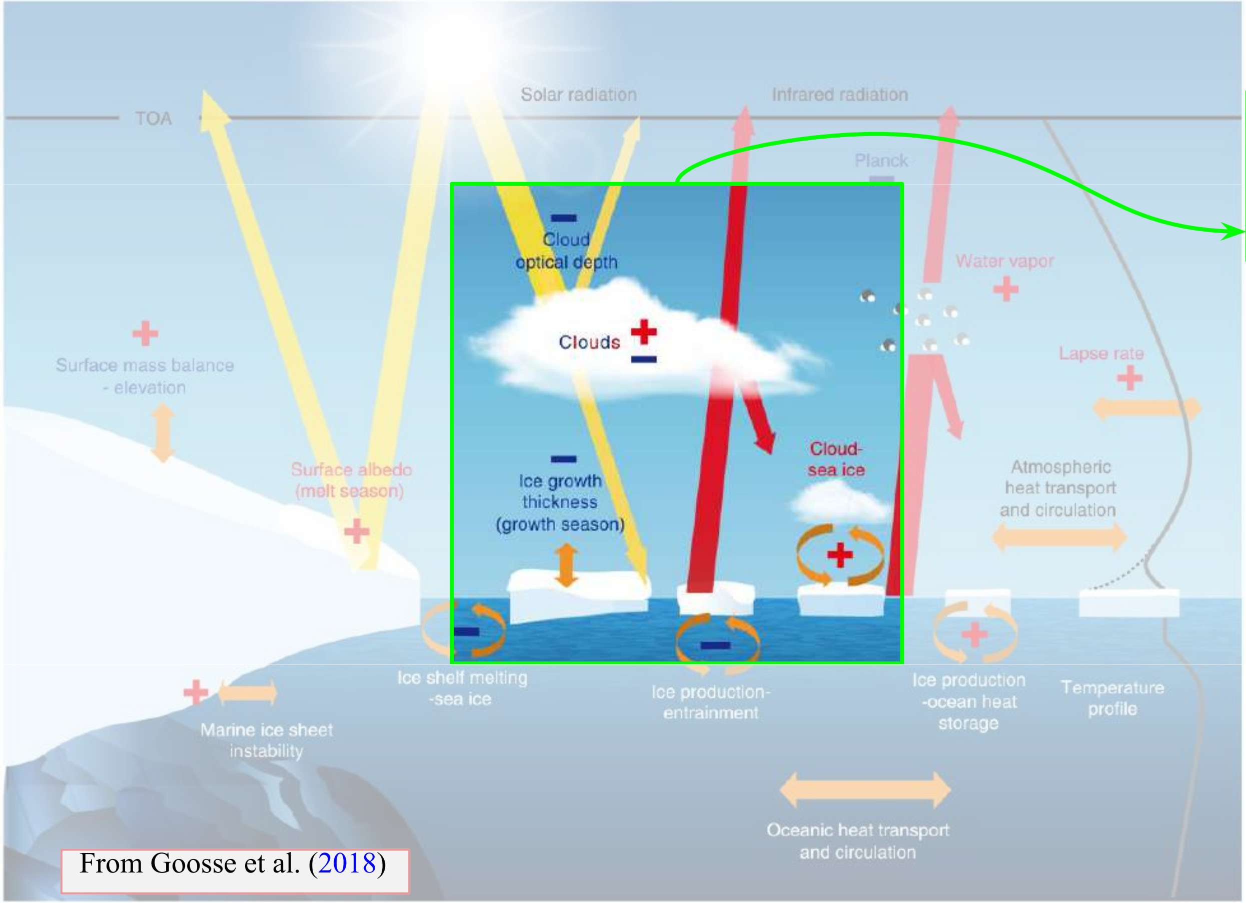


From Windisch et al. (2017)

Over the past 40 years:

- *Arctic has warmed nearly four times faster than the global average (Rantanen et al., 2022)*
- *Larger summer melt and longer melt season (Stroeve et al., 2012, Boisvert & Stroeve, 2015)*
- *More SW absorption in the Arctic ocean and greater ocean warming (Manabe & Stouffer, 1980)*
- *Ocean warming is the driver of Arctic sea ice loss*

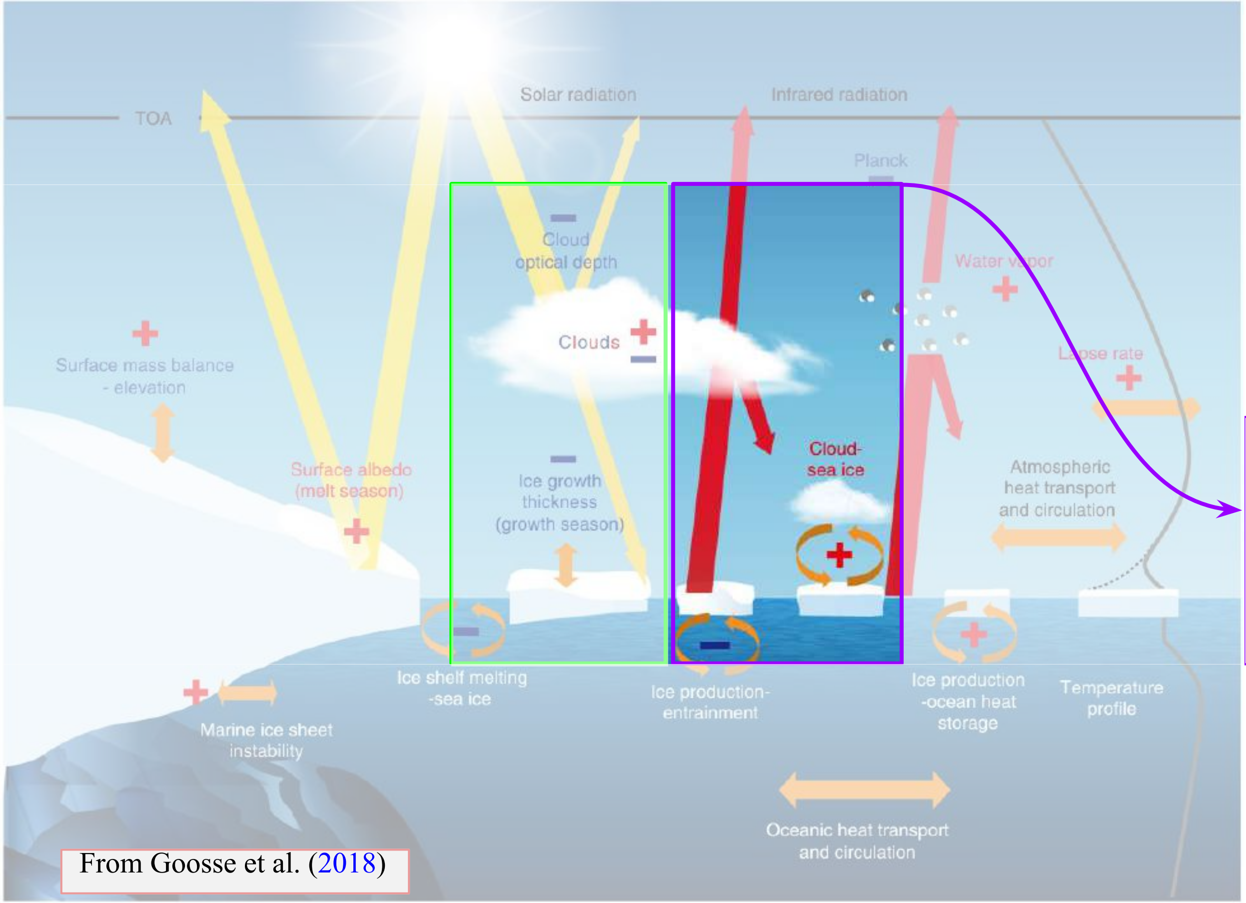
Context: Clouds influence on Arctic's surface energy budget



From Goosse et al. (2018)

- *During **Arctic summer**, any increase in low-level clouds may increase Earth's **albedo** and **dump** sea ice loss.*

Context: Clouds influence on Arctic's surface energy budget

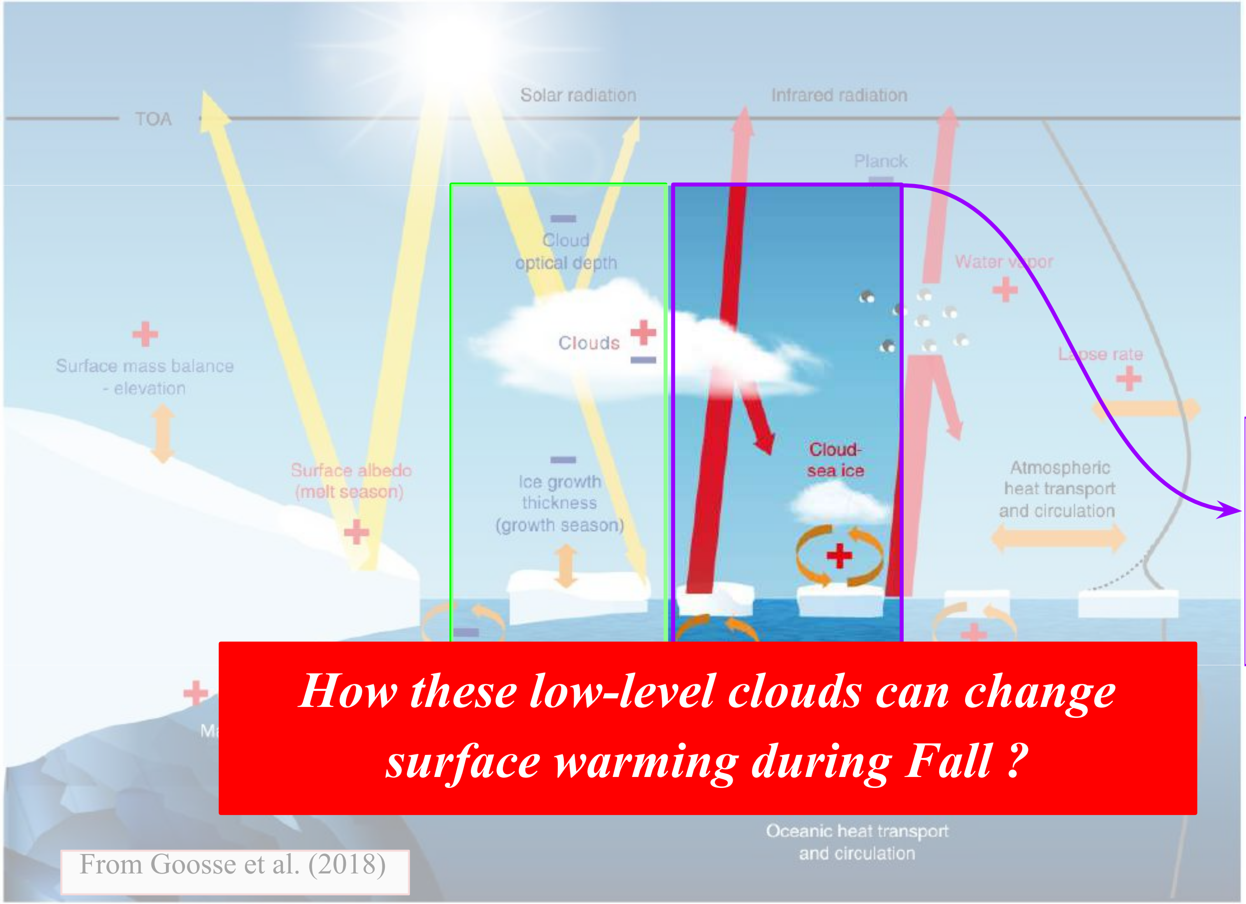


From Goosse et al. (2018)

- *During **Arctic night (non-summer),** any increase in low-level clouds may increase downwelling LW radiation and **amplify** sea ice loss (Kay & Gettelman, 2009; Morrison et al., 2018).*

- *Observations show an increase in **low-level** clouds during **non-summer** seasons (Morrison et al., 2018).*

Context: ***Clouds influence on Arctic's surface energy budget***



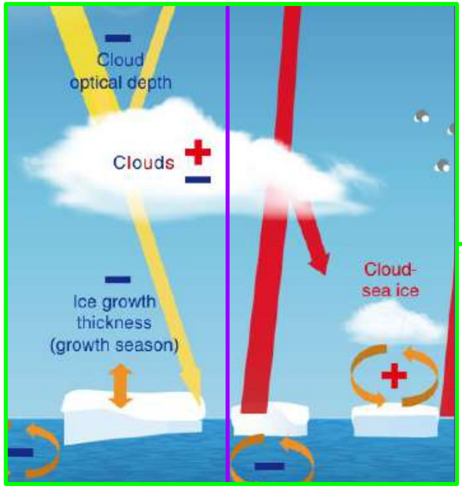
From Goosse et al. (2018)

How these low-level clouds can change surface warming during Fall ?

- *During **Arctic night (non-summer)**, any increase in low-level clouds may increase downwelling LW radiation and **amplify** sea ice loss (Kay & Gettelman, 2009; Morrison et al., 2018).*

- *Observations show an increase in **low-level** clouds during **non-summer** seasons (Morrison et al., 2018).*

Context: Cloud warming and cooling effect on Arctic's surface energy budget

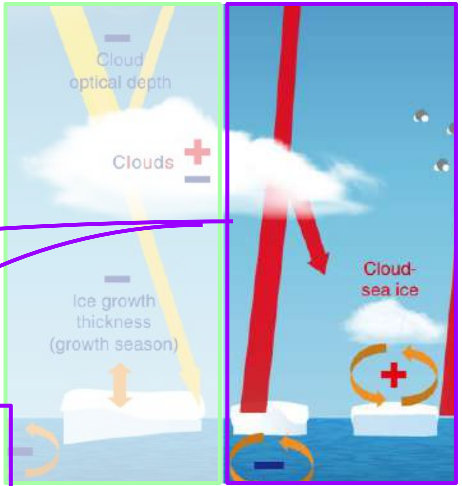


Summer

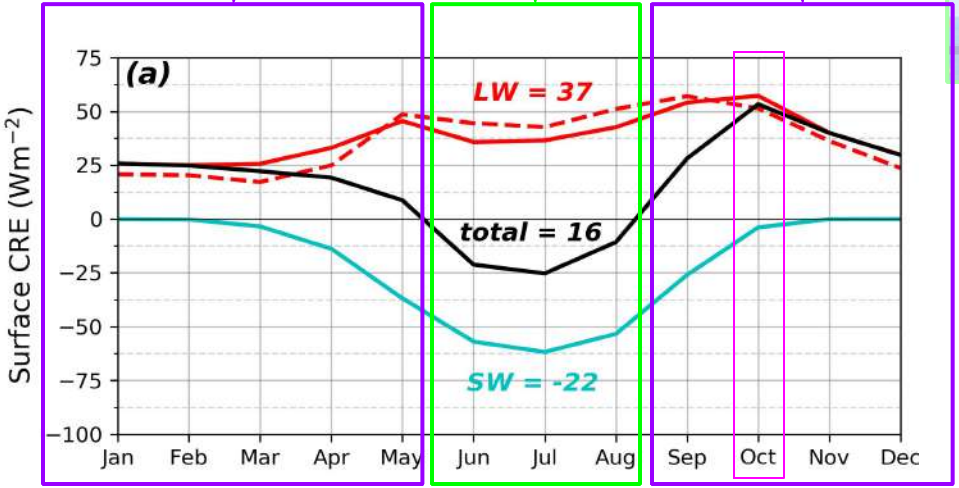
Cooling effect

Non–Summer

Warming effect



Summer
SW dominates

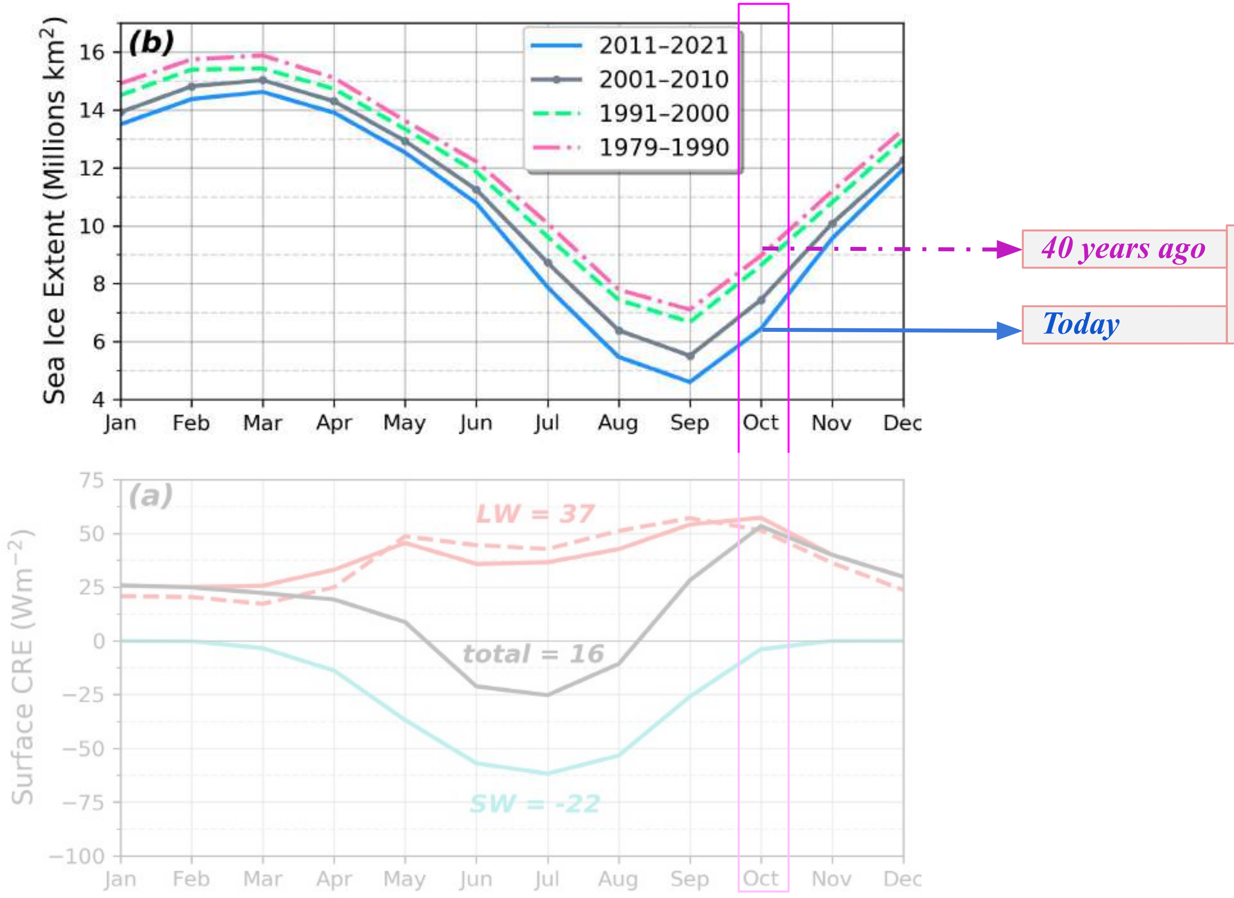


Non–Summer
LW dominates

(Goosse et al., 2018)

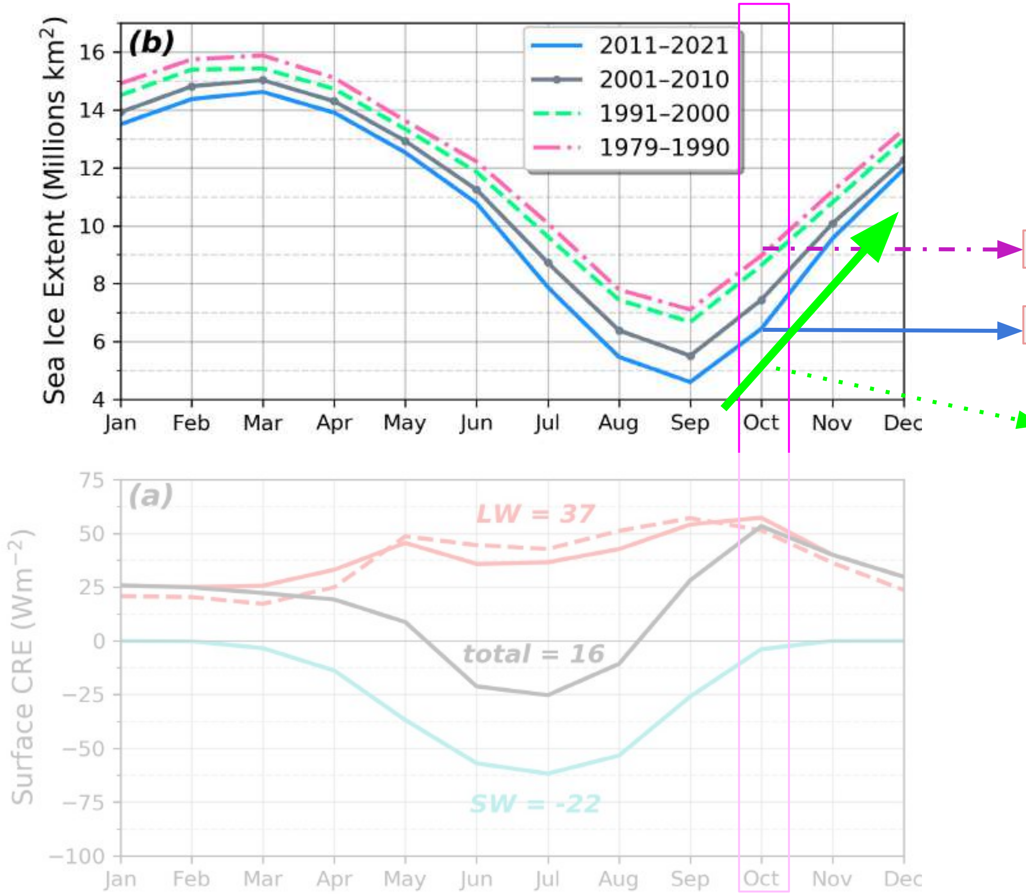
2BFLXHR-Lid
(L'Ecuyer et al., 2019)

Context: October is interesting to investigate the sea ice–surface LW cloud warming co-variability



- ***October** has large Arctic sea ice loss (~ 2.8 millions of km ^{2})*

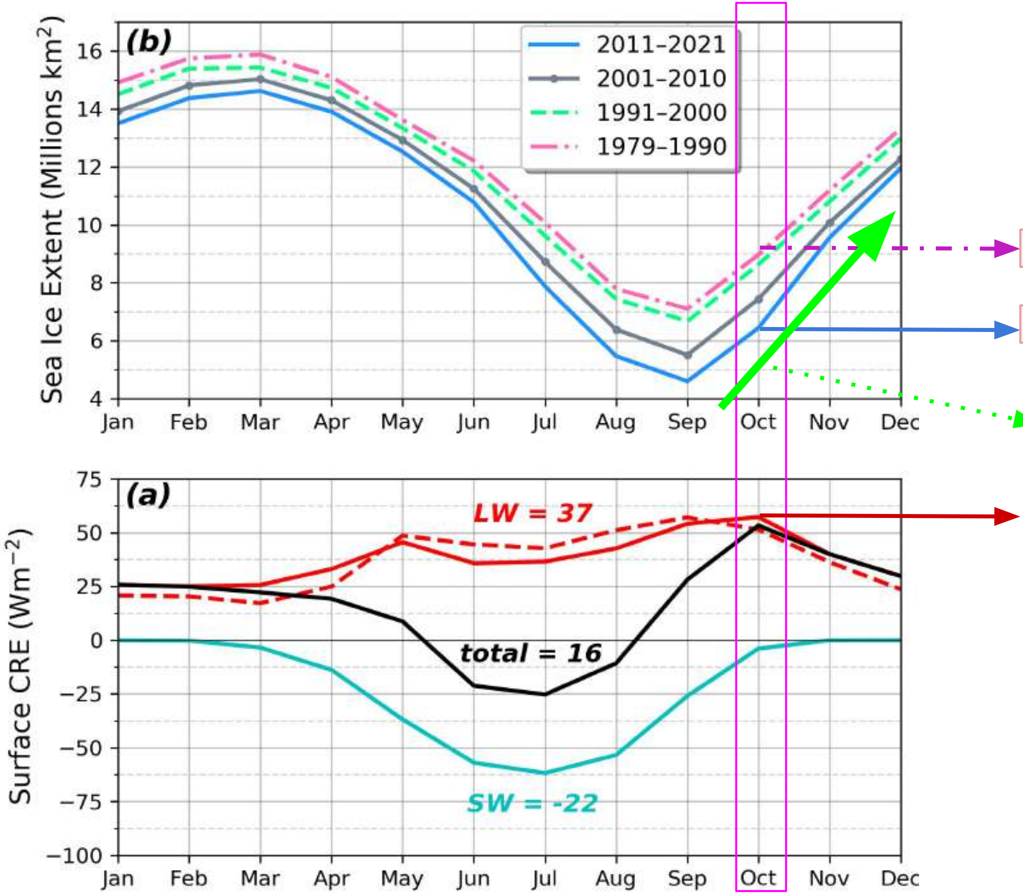
Context: October is interesting to investigate the sea ice–surface LW cloud warming co-variability



- ***October** has large Arctic sea ice loss (~ 2.8 millions of km ^{2})*

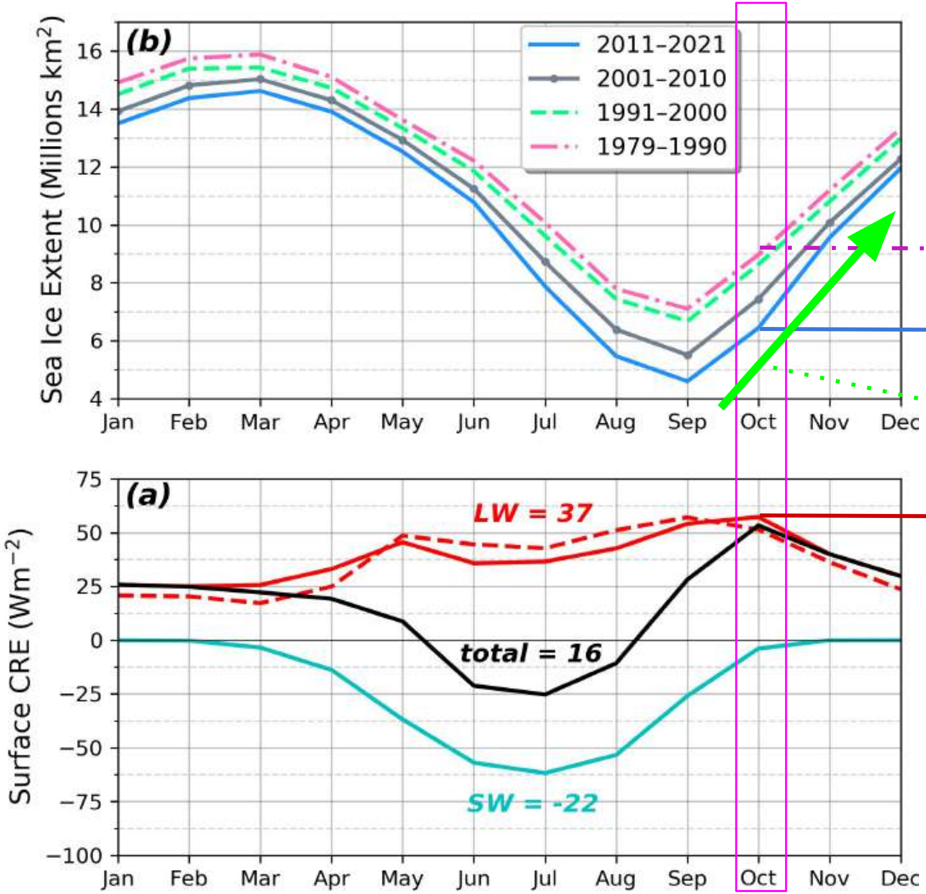
- *During **October**, Arctic sea ice freeze-up*

Context: October is interesting to investigate the sea ice–surface LW cloud warming co-variability



- ***October*** *has large Arctic sea ice loss (~ 2.8 millions of km^2)*
- *During **October**, Arctic sea ice freeze-up*
- *During **October**, clouds warm the surface*
  total CRE = LW CRE

Context: October is interesting to investigate the sea ice–surface LW cloud warming co-variability



40 years ago

Today

- ***October** has large Arctic sea ice loss (~ 2.8 millions of km ^{2})*

- *During **October**, Arctic sea ice freeze-up*

- *During **October**, clouds warm the surface*
  total CRE = LW CRE

Do October clouds delay sea ice freeze-up later into Fall?

Method

Approach

- *Isolate a region where Arctic sea ice cover varies during October.*
- *Look where low-level clouds form the most in response to Arctic sea ice loss.*
- *Quantify the warming effect of clouds at the surface formed in response to Arctic sea ice loss.*
- *Look at the evolution of surface LW cloud warming through Fall.*

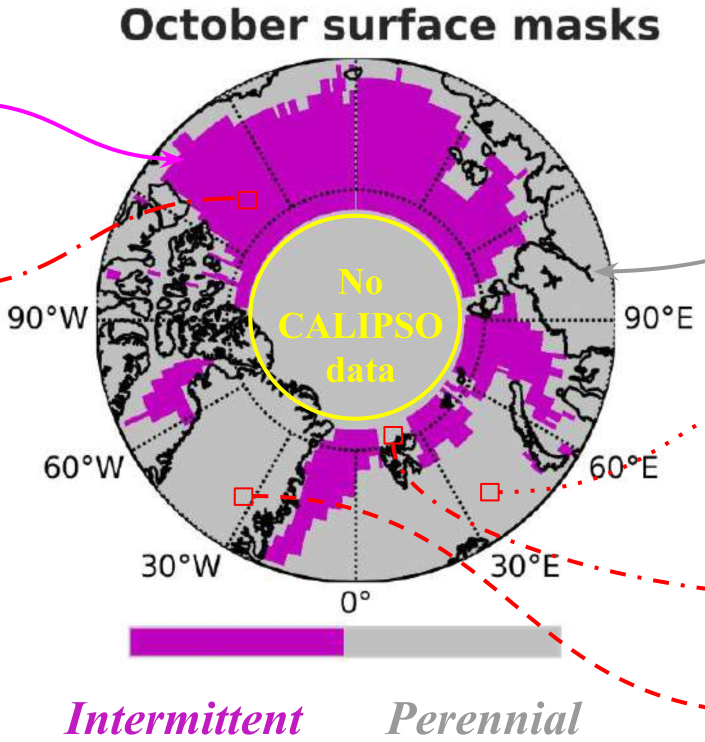
Method: Isolate a region where Arctic sea ice cover varies during October

Intermittent

Daily sea ice cover varies (2008–2020 during October)

- Sea ice cover changes

Day 1, Day 2, ...Day N



Perennial

Daily sea ice cover does not vary (2008–2020 during October)

- Every day ocean

Day 1, Day 2, ...Day N

- Every day ice covered

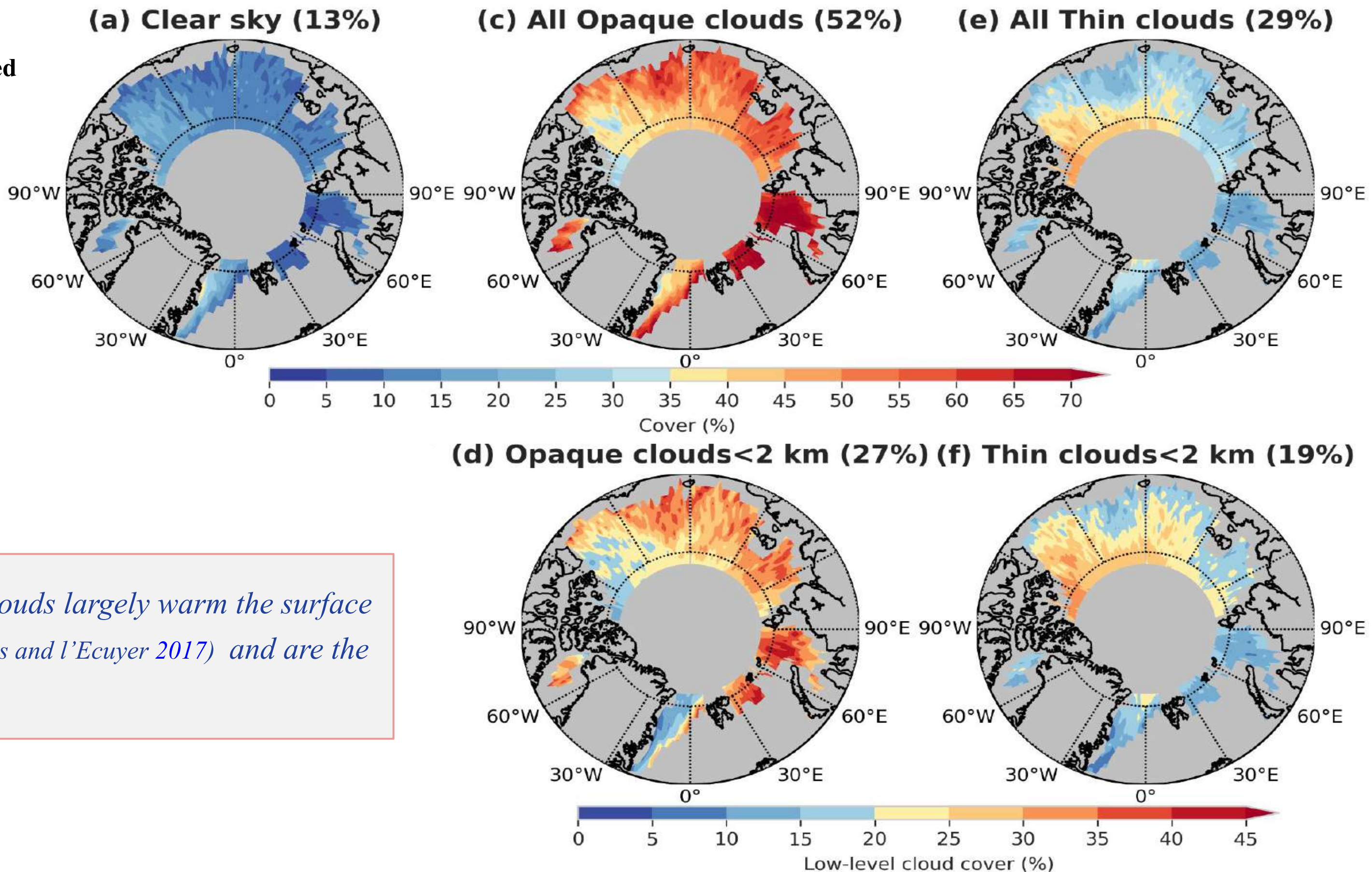
Day 1, Day 2, ...Day N

- Continents

- **Gridded 1°×1°**
- **NSIDC**

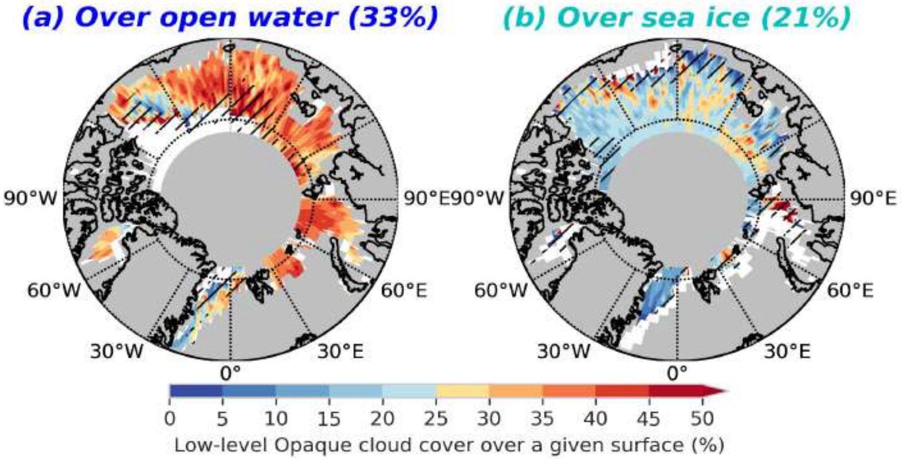
Results: October is very cloudy throughout the entire intermittent mask

- **Along orbit track Gridded 1°×1°**
- **2008-2020**



- *Low-level opaque clouds largely warm the surface (Arouf et al. 2022; Matus and l'Ecuyer 2017) and are the numerest (27 %).*

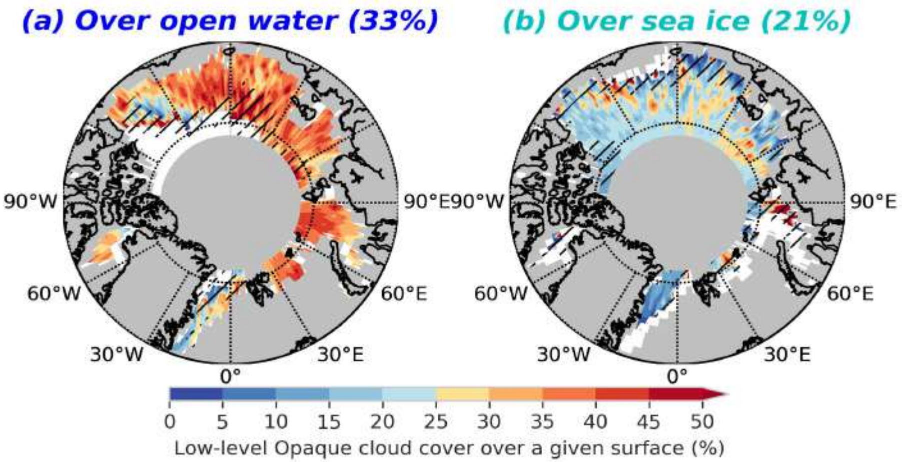
Results: Low-level opaque clouds are more numerous over open water than over sea ice



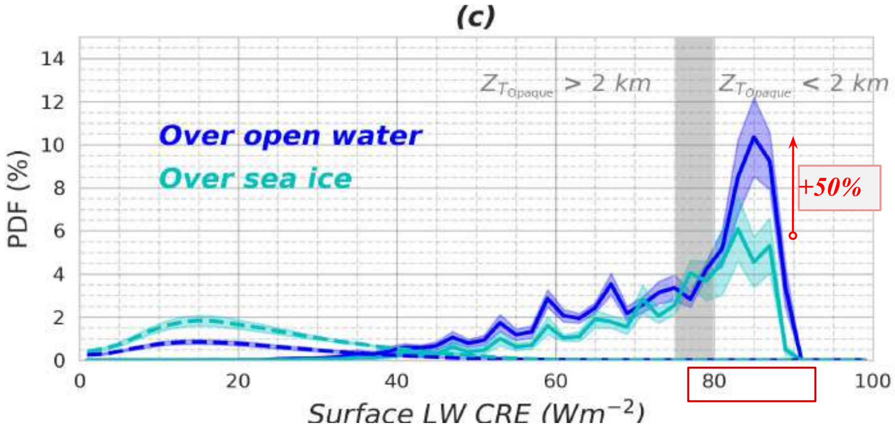
- **Along orbit track gridded on 1°×1°**
- **2008-2020**

•Intermittent mask is a region where we assume that sea ice variability affects more low-level clouds than large scale atmospheric circulation (Morrison et al., 2018).

Results: Large surface LW CRE are much more frequent over open water than over sea ice



- **Along orbit track gridded on 1°×1°**
- **2008-2020**

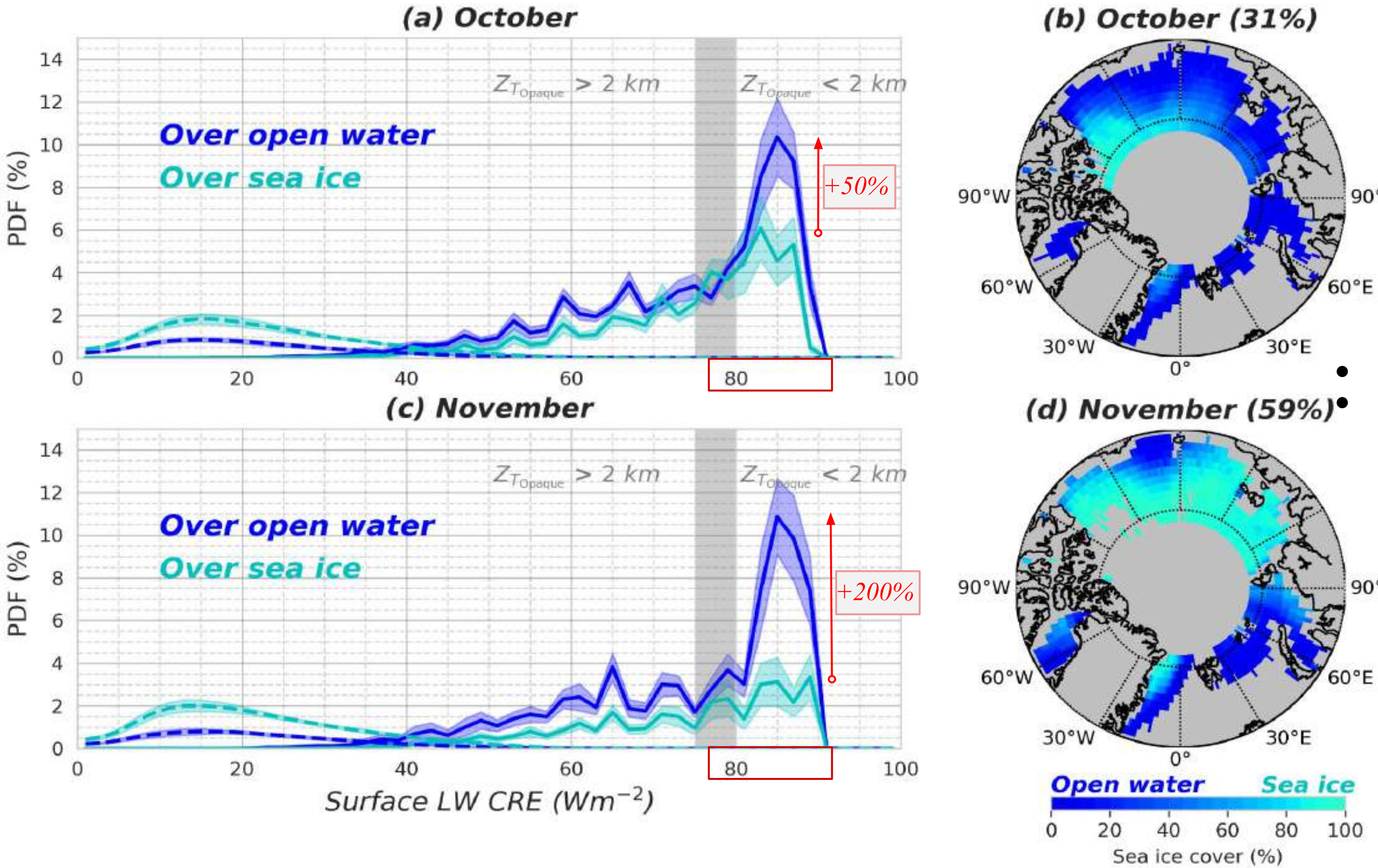


(c) Accumulating 13 years of orbit data (possible with LWCRE–LIDAR)

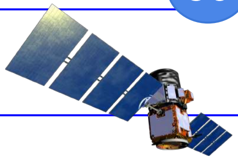
Large surface LW cloud warming (CRE > 80 W m $^{-2}$) occurs +50% more often over open water than over sea ice.

Results: More large surface cloud warming as open water persists later into Fall

Accumulating orbit data (2008-2020)



- Gridded 1°×1°
- 2008-2020



Second conclusions

High values of surface LW cloud warming (> 80 W m^{-2}) occur ~ +50% (+200%) more often over open water than over sea ice during October (November) months.

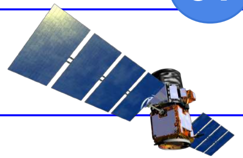
As the climate warms up due to human activities, clouds would contribute to lengthen the melt season by potentially delaying ice freeze-up later into the Fall.

manuscript submitted to *Geophysical Research Letters*

Surface cloud warming increases as Fall Arctic sea ice cover decreases

Assia Arouf[1], Hélène Chepfer[1], Jennifer E. Kay[2,3], Tristan S. L'Ecuyer[4], Jean Lac[1]

General conclusions

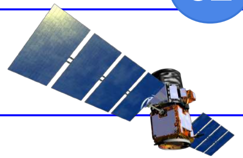


I **Surface LW cloud warming over more than a decade from CALIPSO lidar observation**

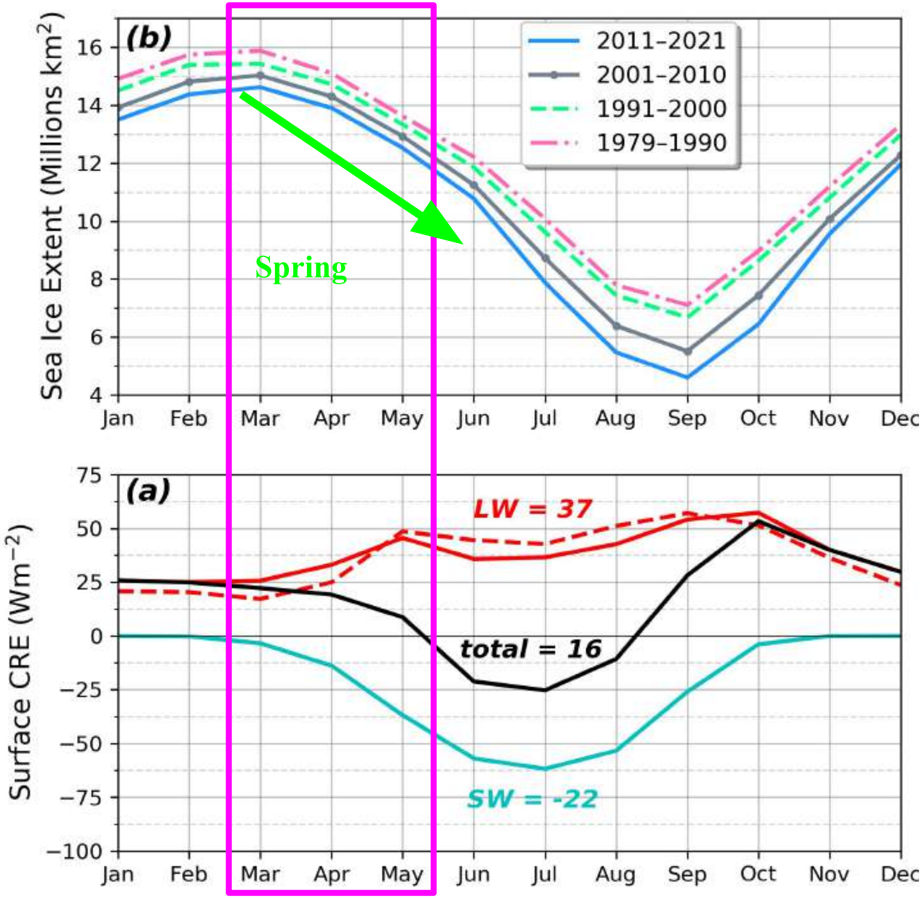
CALIPSO observations allowed us to retrieve the surface LW CRE over 13 years and to study its variability. This retrieval might be lengthen with future spaceborne lidars (e.g. EarthCARE)

II **Link between surface LW cloud warming and Arctic sea ice loss**

Clouds warm the surface in response to sea ice loss (surface LW CRE > 80 W m^{-2}) and may delay sea ice freeze-up later into the fall as climate warms up.



Perspective 1: Do clouds help to set up the sea ice melt onset during Spring?

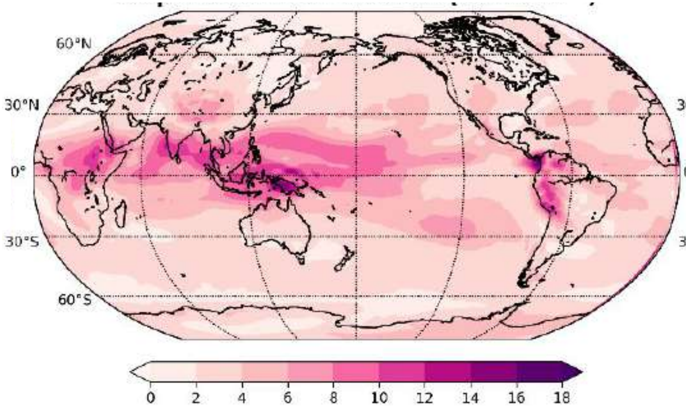


(Huang et al., 2019)

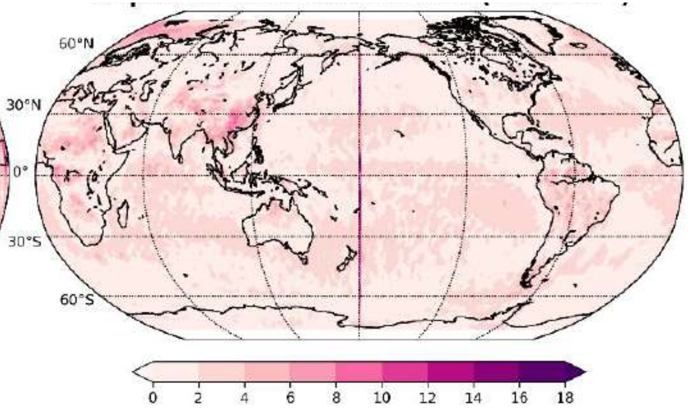
Perspective 2: Evaluate surface LW CRE in CMIP6 climate models

TOA

Inter-**models** spread (**4.0** W m^{-2})

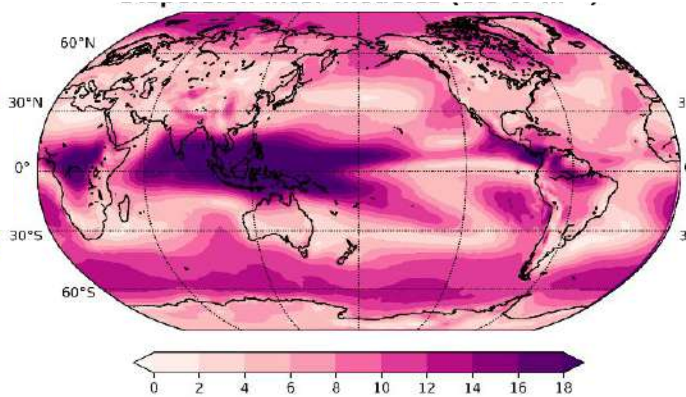


Inter-**observations** spread (**1.8** W m^{-2})

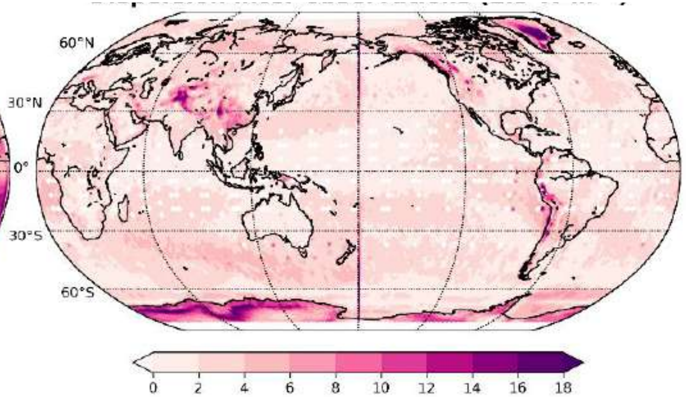


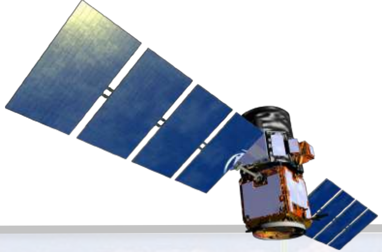
Surface

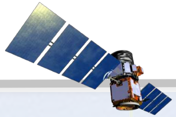
Inter-**models** spread (**8.5** W m^{-2})



Inter-**observations** spread (**2.5** W m^{-2})







Surface longwave cloud radiative effect derived from

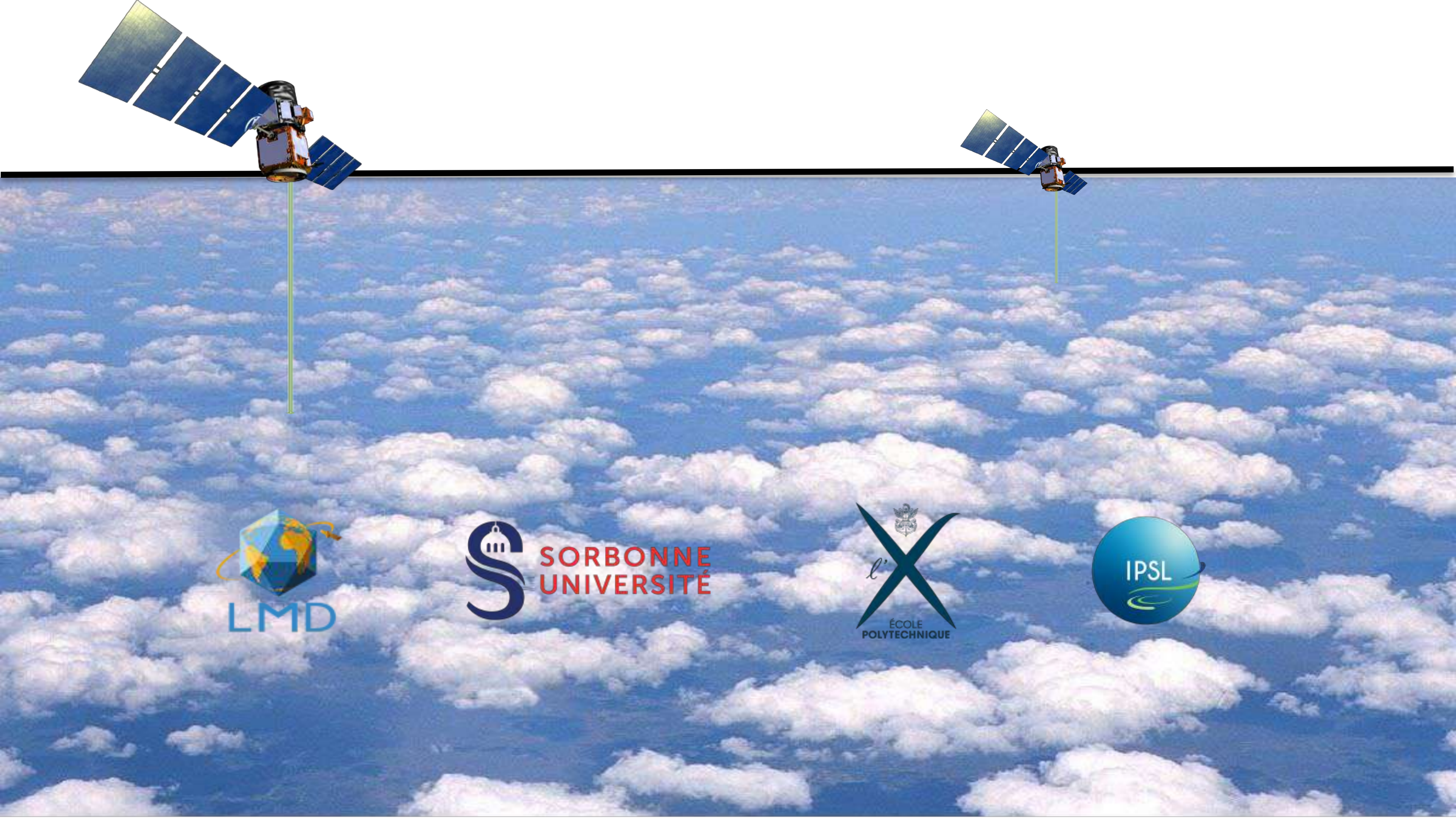
space lidar o cation in the Arctic

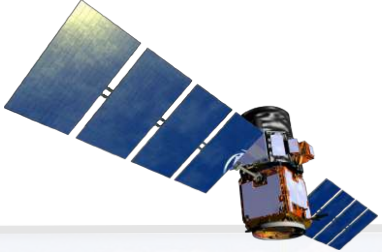
Thank you!

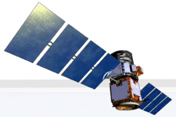
April 21st, 2023: PhD defense

Assia Arouf

Supervisor: Hélène Chepfer


LMD
SORBONNE
UNIVERSITÉ
l'X
ÉCOLE
POLYTECHNIQUE
IPSL





Surface longwave cloud radiative effect derived from space lidar observations: application in the Arctic

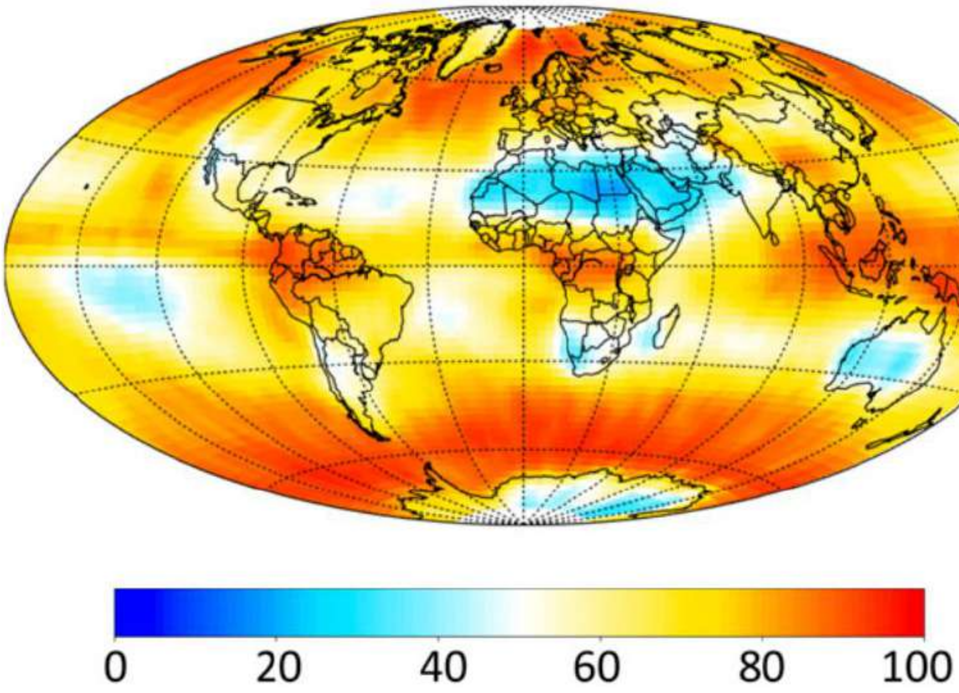
Annex Context

April 21st, 2023: PhD defense

Assia Arouf

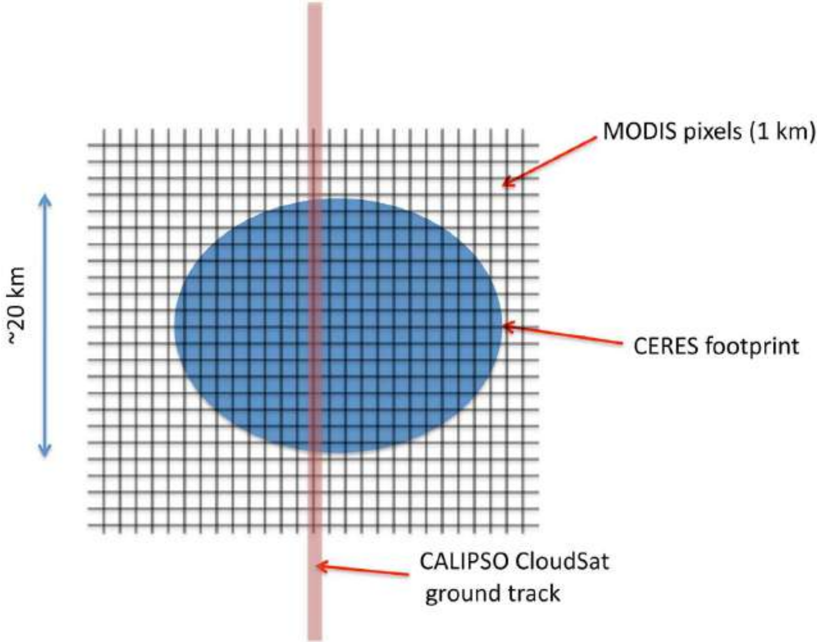
Supervisor: Hélène Chepfer

Cloud fraction



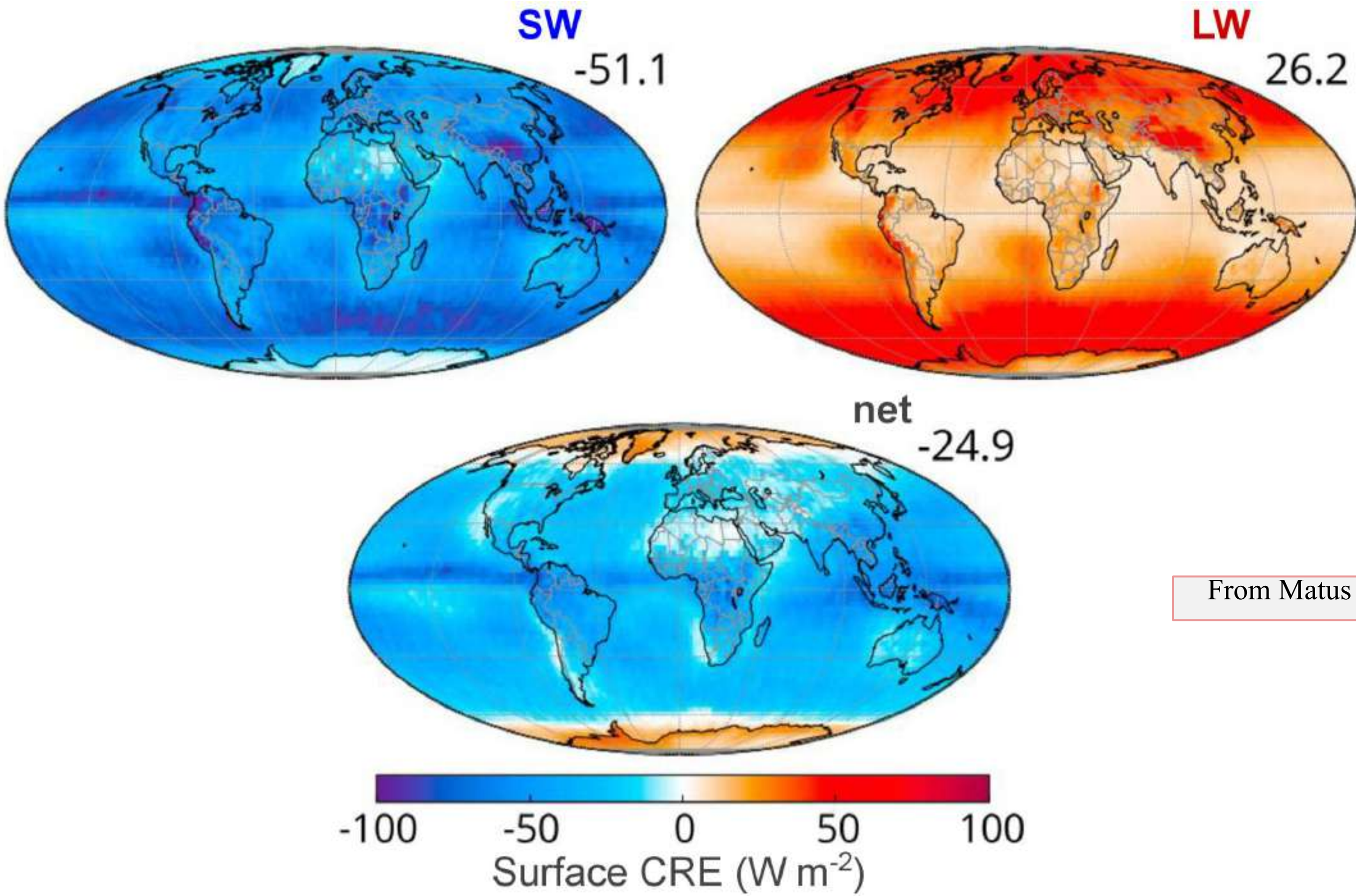
From L'Ecuyer et al. (2019)

CERES CCCM footprints



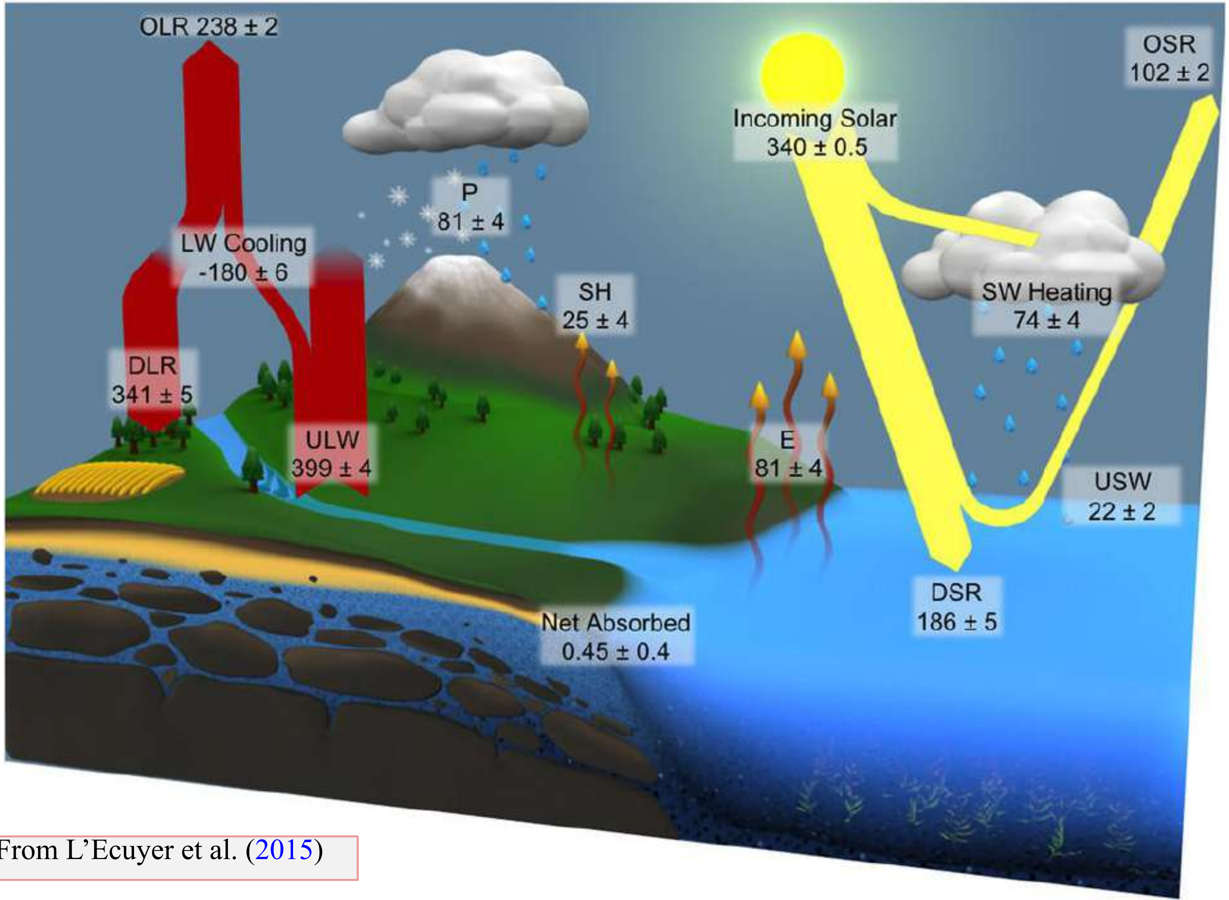
From Kato et al. (2011)

Surface SW, LW, Net CREs

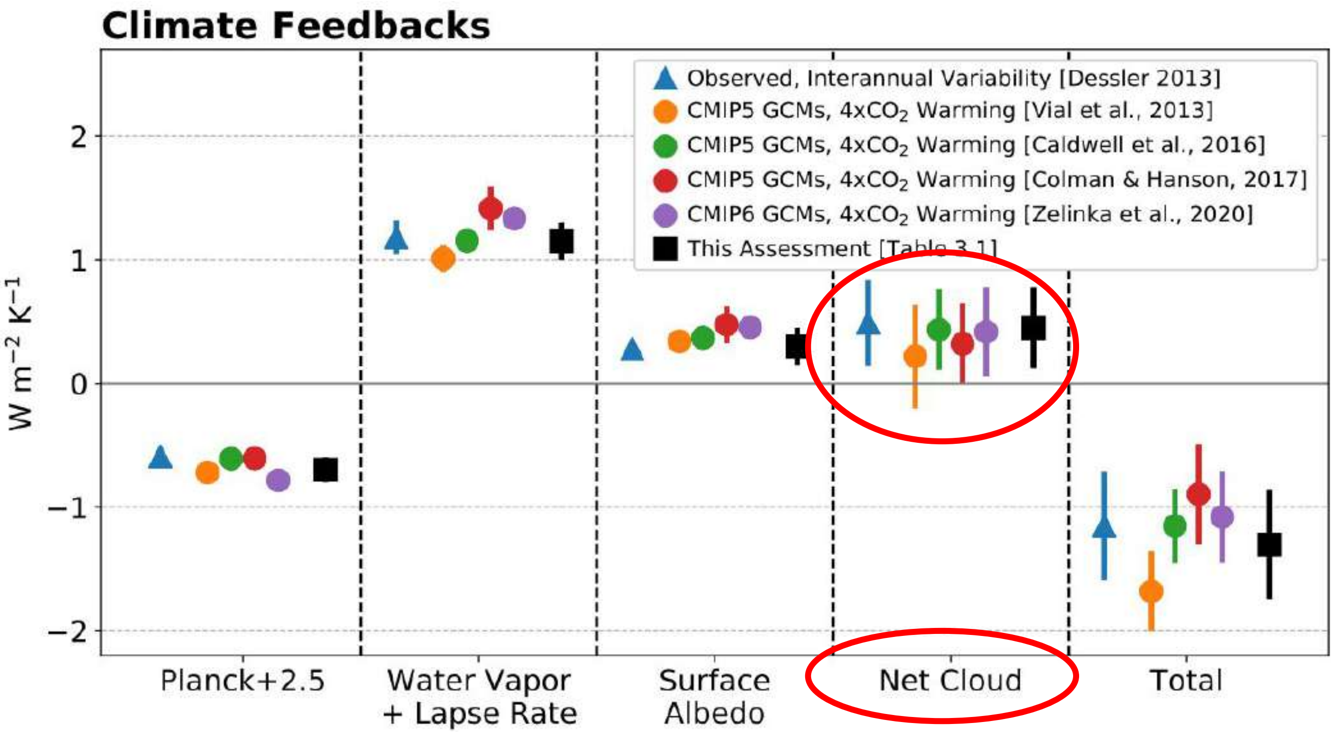


From Matus and L'Ecuyer (2017)

Earth energy budget (2000–2009)



From L'Ecuyer et al. (2015)

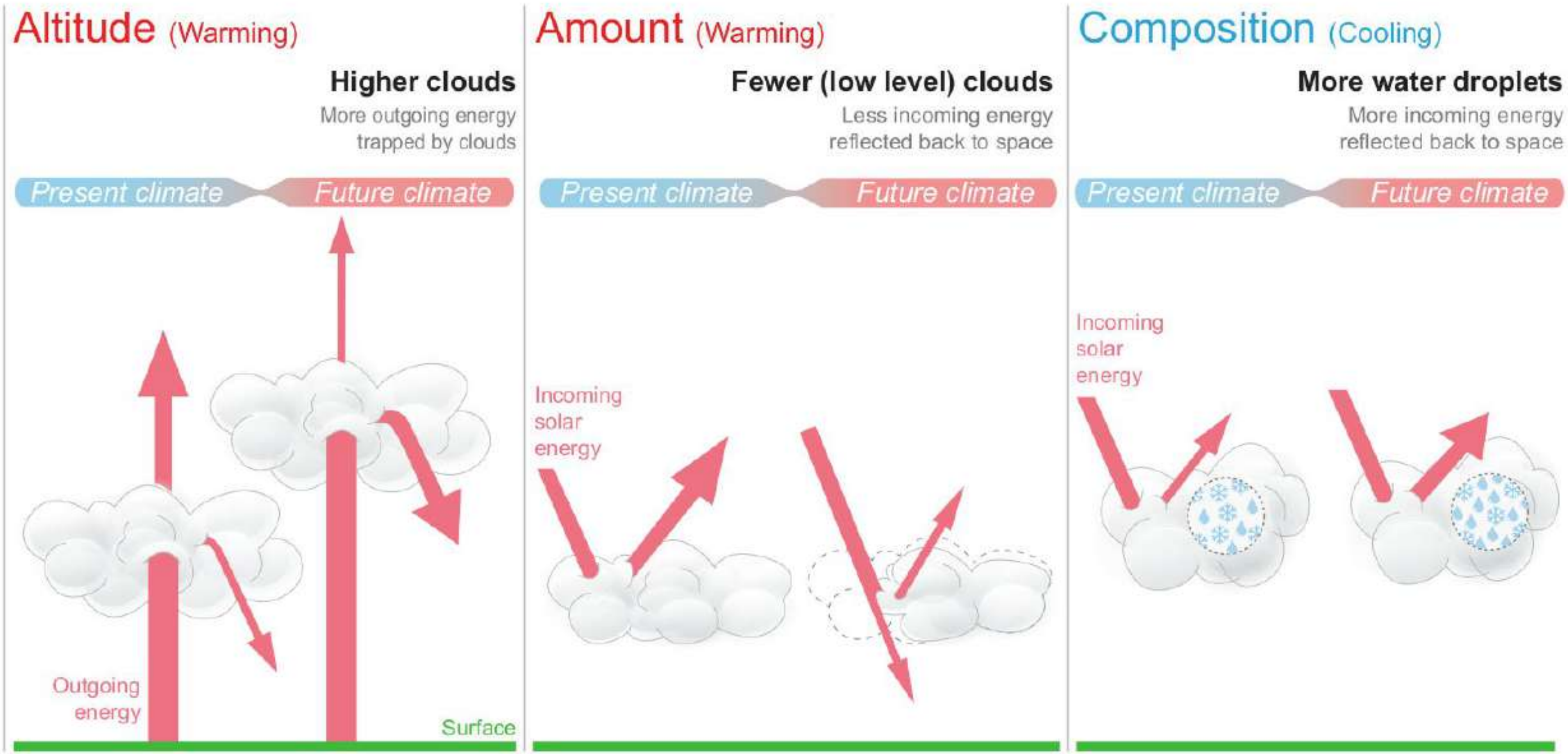


From Sherwood et al. (2020)

Large uncertainties in cloud feedbacks

FAQ 7.2: **What is the role of clouds in a warming climate?**

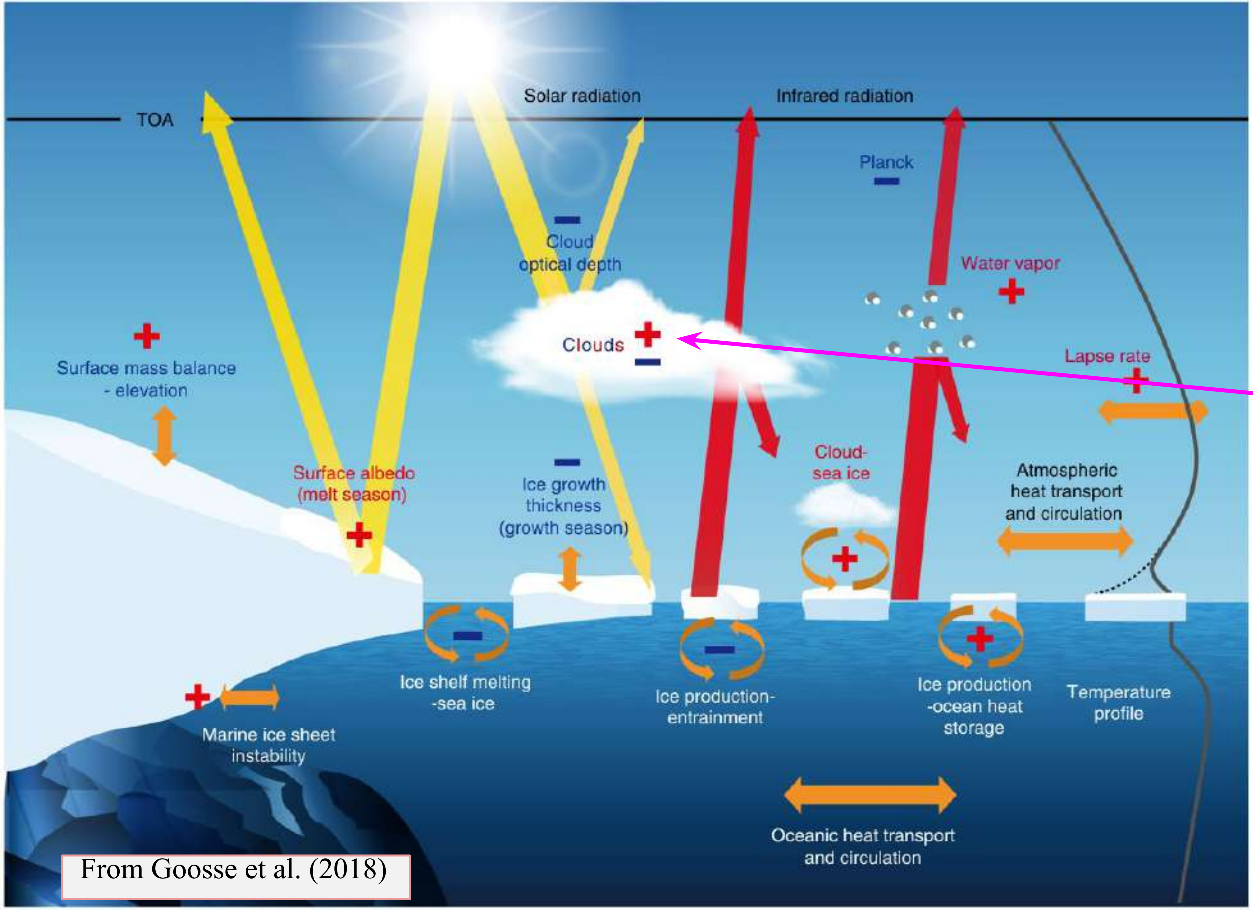
Clouds affect and are affected by climate change. Overall, scientists expect clouds to **amplify future warming**.



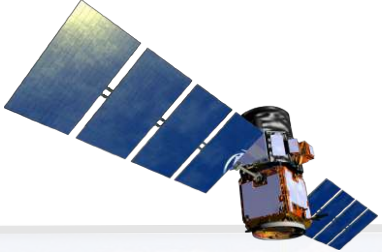
From IPCC (2021)

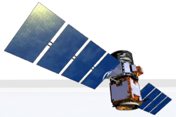
Do observations detect these changes in cloud properties?
=> Need observations from active remote sensing instruments **stable in time** and **well calibrated**

Feedbacks



Both positive and negative feedback





Surface longwave cloud radiative effect derived from space lidar observations: application in the Arctic

Annex Tools

April 21st, 2023: PhD defense

Assia Arouf

Supervisor: Hélène Chepfer

SORBONNE UNIVERSITÉ

ÉCOLE POLYTECHNIQUE

IPSL

Lidar: télédétection active = émet sa propre source de rayonnement

CALIPSO

Lancé 28/4/2006

Altitude : 700 km   // dans la constellation **A-Train**

Inclinaison : 98.2°

Un tour de la terre : 99 min

CALIOP :

Rétrodiffusion élastique (sans changer la longueur d'onde)

Longueur d'onde 532 et 1064

Seule la diffusion élastique par les molécules et particules affecte le signal.

Téléscope : 1m, empreinte sol 90 m

Angle de tire : 3°/ au nadir (0.3° avant nov 2007)

Echantillonnage horizontal : 333 m

GOCCP

conçu pour évaluer la représentation des nuages dans les modèles de climat

résolution verticale : 480 m

Detection nuage : $SR = ATB_{480} \backslash ATB_{480}mol$

Signal complètement atténué : $tau_{vis} = 3\text{-}5$

$Tau_{VIS} = 2^{*} tau_{IR}$

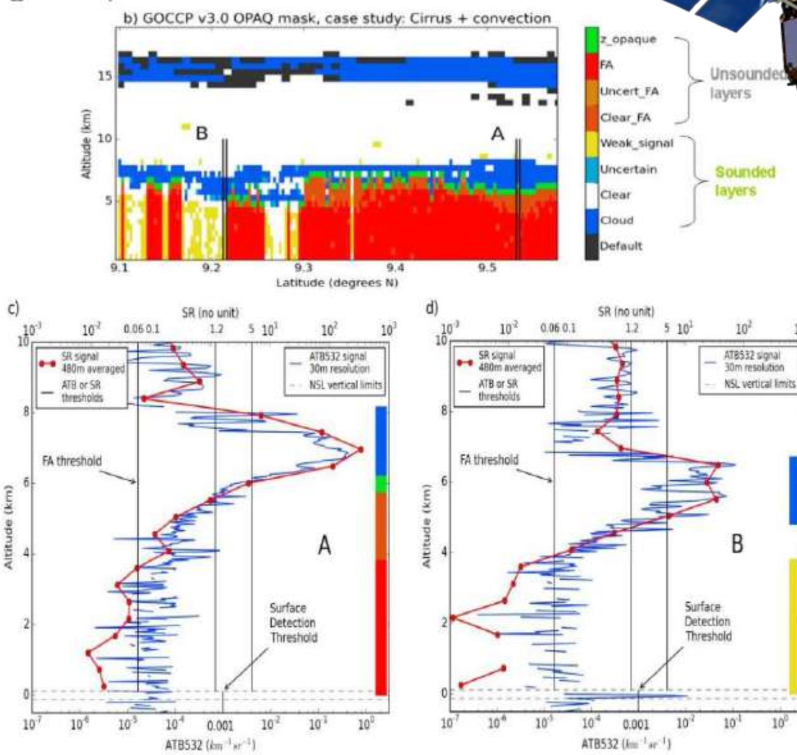
Limites

Ne voit pas en dessous de Z_{FA}

uncertainties in the atmospheric state variables from the ERA-I

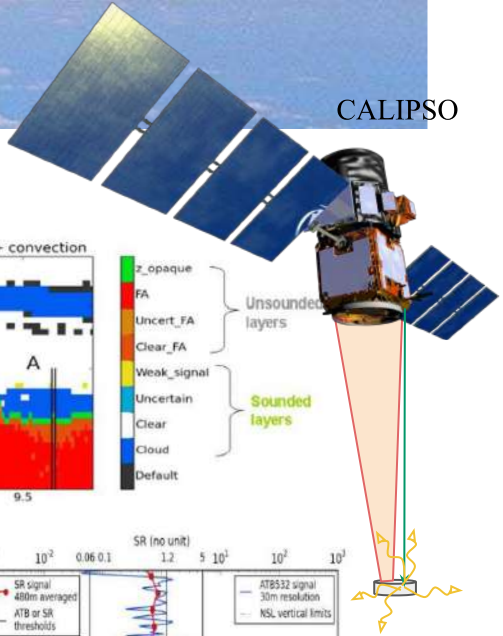
$\varepsilon_{Thin} = 1 - e^{-\tau\ \text{-}IR}$ (eg. Vaillant de Guélis et al., 2017a).

(Guzman et al., 2017)

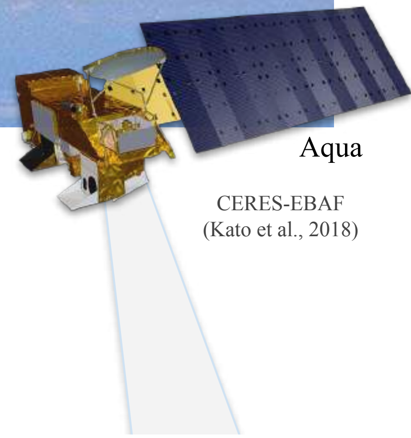


Opaque cloud

Thin cloud



Radiomètre: télédétection passive = mesure le rayonnement naturel



Aqua

CERES-EBAF
(Kato et al., 2018)

AQUA

Lancé : 4 mai 2002

Dans la constellation **A-Train**

CERES :

Radiomètre spatial estime le bilan radiatif au TOA

3 canaux en bande large.

- Rayonnement total entre 0,3 µm et 200 µm
- rayonnement visible et P-IR entre 0,3 µm et 5 µm
- 8 µm et 12 µm (transparence de l'atmosphère)

empreinte sol 20 km

Mesure une luminance (W/m2/sr) puis convertis en Fluw (W/m2)

Balayage horizontal le long de sa trace

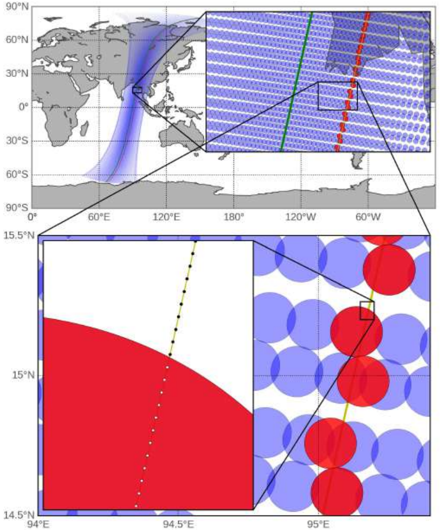
CERES EBAF

Utilise MODIS pour détecter les nuages (résolution plus fine)

Geostationary imager (1h, 60°S - 60°N) are also used to account for cloud-radiation changes between CERES observation times.

CERES CCCM **(CALIPSO, CloudSat, CERES, and MODIS Merged Product ; KATO et al., 2011)**

SSF se trouve sur la trajectoire de CALIPSO (60 profils calipso)



Limites

- Positive bias of cloud fraction over high elevation regions. In particular, low-mid and high-mid cloud fractions are biased high over the Summit site except for summer time (Kato et al. rapport 2020).

-trend analyses with surface fluxes over polar regions from Ed4.0 EBAF-Surface should be avoided.

Radar : télédétection active = émet sa propre source de rayonnement

CloudSat

2BFLX
(L'Ecuyer et al., 2019)

CloudSat

Lancé 28/4/2006

Fin : avril 2011 à cause d'une anomalie de batterie de CloudSat

Dans la constellation **A-Train**

CPR :

un radar à visée nadir de 94 GHz
Résolution verticale 500 m

Empreinte sol 5 km

2BFLX

CALIOP provide properties for clouds and aerosol undetected by CloudSat
MODIS based 2B-TAU to obtain the optical depth and mean effective radius of single layer clouds

Limites

-Only 5 years during nighttime

-"CloudSat CPR's long powerful pulse also generates a surface clutter echo which tends to partially mask signals from cloud and precipitation forming below circa 1 km (Marchand et al., 2008)"

- the largest sources of LW flux uncertainty are prescribed surface temperature and lower-tropospheric humidity (HENDERSON et al 2013) (atmospheric state variables from the ECMWF-AUX)

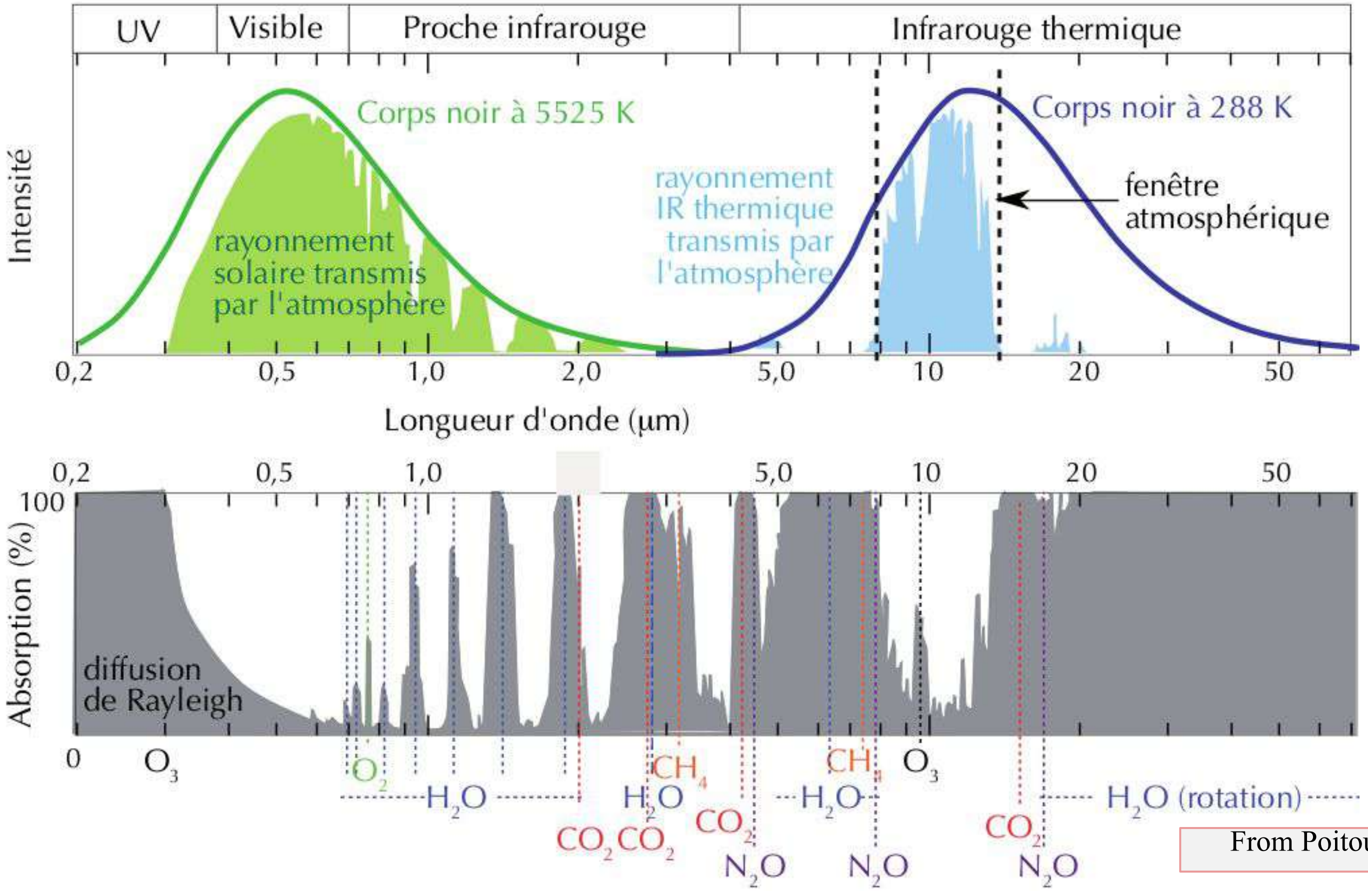
GAME : radiative transfer code

GAME (Dubuisson et al., 2004)

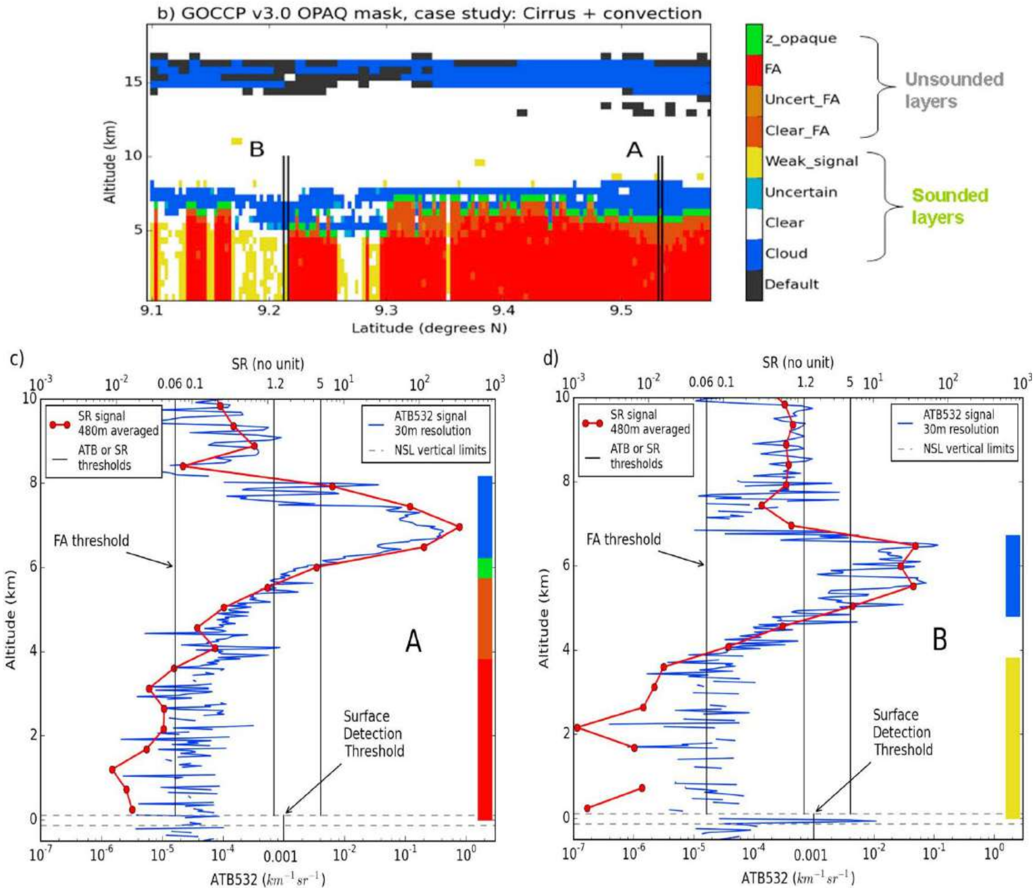
Simule l'interaction matière rayonnement dans l'atmosphère.
Prend en compte la diffusion multiple
C'est un code à bande étroite (bande de 20 cm-1)
Approximation plans-parallèles infinis
Résolution verticale de 1 km (entre 0 et 25 km)
On utilise le rayonnement simulé entre 5µm et 200µm (même que CERES)
Emissivité de surface 0.98 Ocean // 0.5 Land
CO2, CH4, CO fixe dans game (gaze stable)

On fait varier :
La température de surface
Les profils d'humidité, de température, de pression et d'ozone de 0 à 120 km.
Profils T, vapeur d'eau sont extrai des réanalyse de 0km à 45 km.
Ozone, 0km à 120 km, T, Vap de 45km à 120 km proviennent de AFGL.
Profil de nuage en spécifiant le type de particule nuageuse, distribution de taille et l'épaisseur optique dans chaque couches de nuages.

Réanalyses :
Données issus d'un modèle de prévision météorologique et d'observations
Permet d'avoir un portrait global du système Terre depuis 1979.



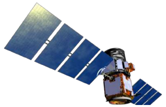
From Poitou et al. (2013)



From Guzman et al. (2017)

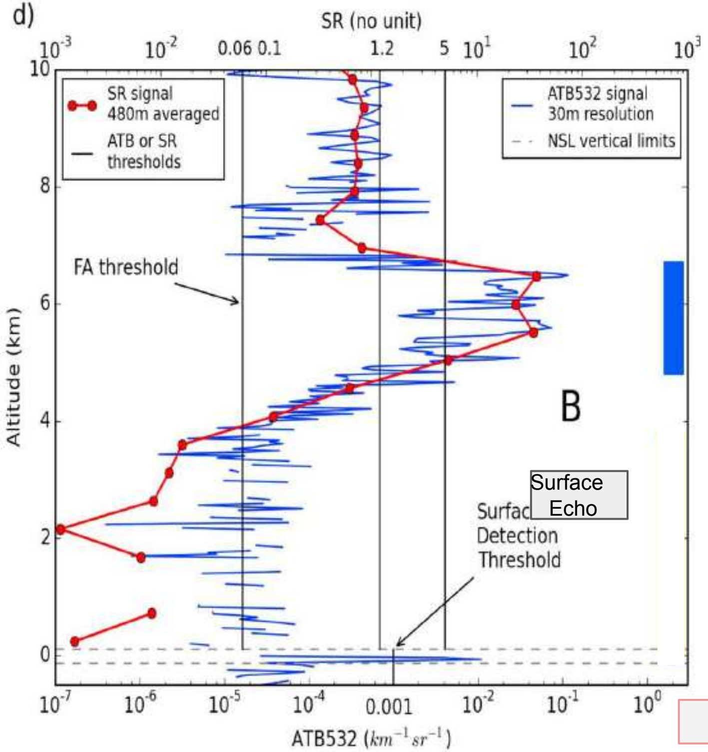
Tools: CALIPSO LW Emissivity retrieval

Annex emissivity



CALIPSO

- **90 m/330 m along orbit track**
- **2006–2022**
- **Surface independent**
- **Thick/Thin**



Cloud

From Guzman et al. (2017)

$$SR(z) = \frac{ATB_{480m}(z)}{ATB_{480m,mol}(z)}$$

$$\tau_{app}^2 = \frac{\tilde{SR}_{below}}{\tilde{SR}_{above}}$$

$$\tau_\lambda = e^{(-\delta_\lambda \quad)}$$

$$\delta_{VIS} = \delta_{app}/\eta,$$

$$\delta_{VIS} = 2 * \delta_{IR}$$

$$\varepsilon_{Thin} = 1 - e^{-\delta_{Thin}^{LW}}$$

(Vaillant de Guélis et al., 2017a
Garnier et al., 2015)

Restitution emissivity

- Interaction radiation object :

$A+R+\tau = 1$

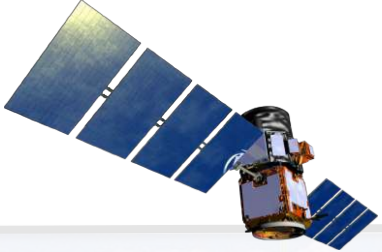
in IR : R=0 $\Rightarrow$ $A+\tau=1$ $\Rightarrow$ $A=1-\tau$

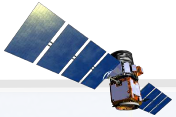
optical depth $\delta_{VIS} = 3$ to 5 for opaque clouds (depending on cloud microphysical properties : liquid particle are smaller than ice particles and therefore reflect more SW rad back to space and attenuates at optical depth smaller (3))

$\varepsilon = A$ and $\tau = \exp(-\delta)$ and $\delta_{VIS} = 2^* \delta_{IR}$

$$\Rightarrow \varepsilon_{IR} = 1-\exp(-\delta_{IR}) \Rightarrow \varepsilon_{IR} = 1-\exp(-1.5)=0.80 \,//$$

$$\varepsilon_{IR} = 1-\exp(-2.5)=0.99$$





Surface longwave cloud radiative effect derived from space lidar observations: application in the Arctic

Annex RT computations

April 21st, 2023: PhD defense

Assia Arouf

Supervisor: Hélène Chepfer

Surface LW cloud radiative effect equations

$$CRE_{SFC,\,LW} = (F^{\downarrow} - F^{\uparrow})_{All\text{-}Sky,\,LW} - (F^{\downarrow} - F^{\uparrow})_{Clear\text{-}Sky,\,LW}$$

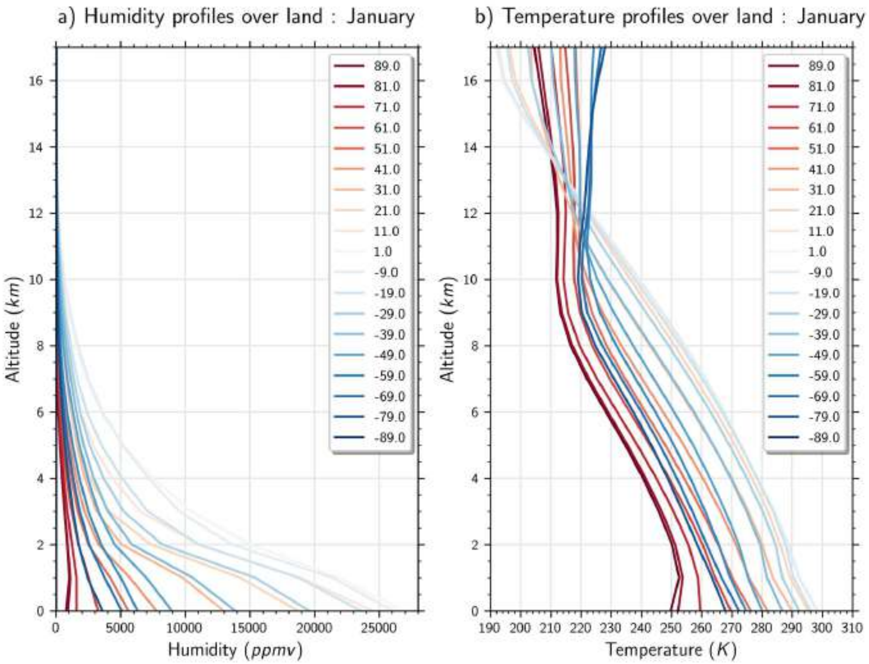
$$CRE_{SFC,\,LW} = (F^{\downarrow}_{All\text{-}Sky,\,LW} - F^{\downarrow}_{Clear\text{-}Sky,\,LW}) - (F^{\uparrow}_{All\text{-}Sky,\,LW} - F^{\uparrow}_{Clear\text{-}Sky,\,LW})$$

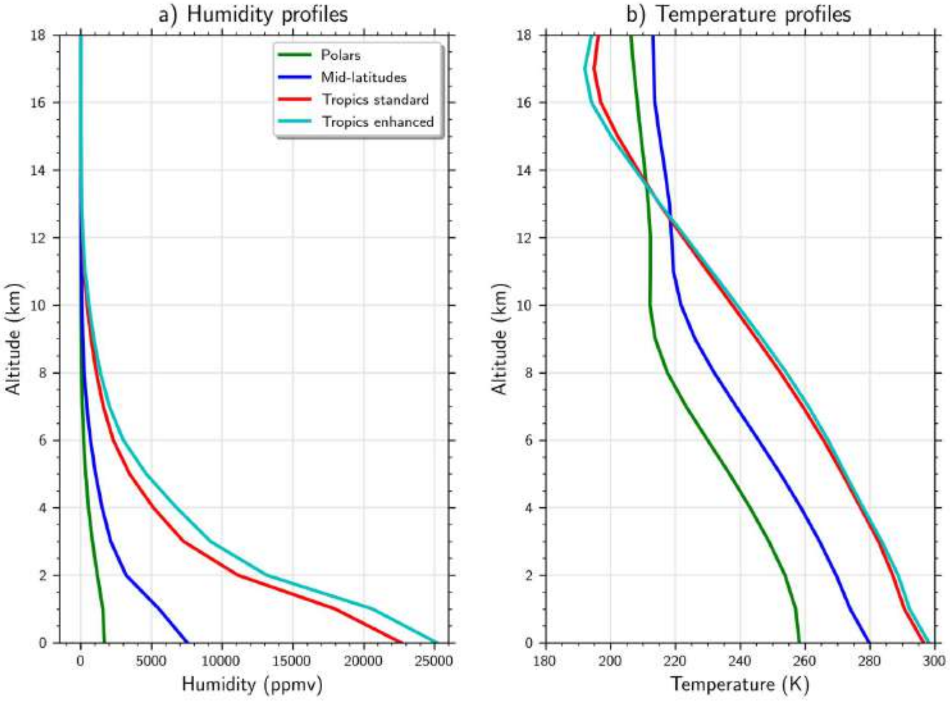
$$CRE_{SFC,\,LW} = \underbrace{(CRE^{\downarrow}_{SFC,\,LW})}_{\text{The driver}} - \underbrace{(CRE^{\uparrow}_{SFC,\,LW})}_{\simeq 1\ W\ m^{-2}}$$

The driver

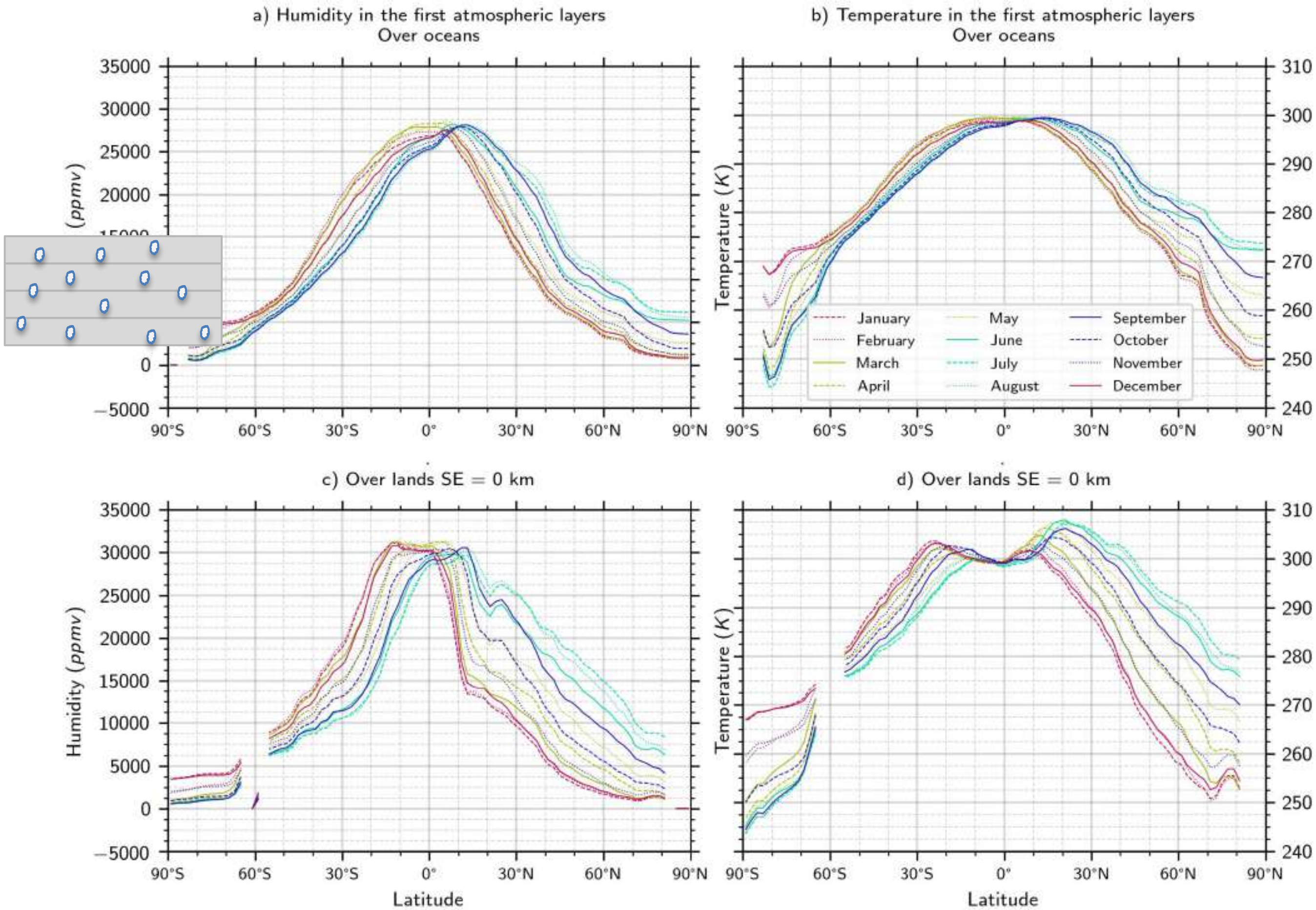
$\simeq 1\ W\ m^{-2}$

Humidity and temperature profiles

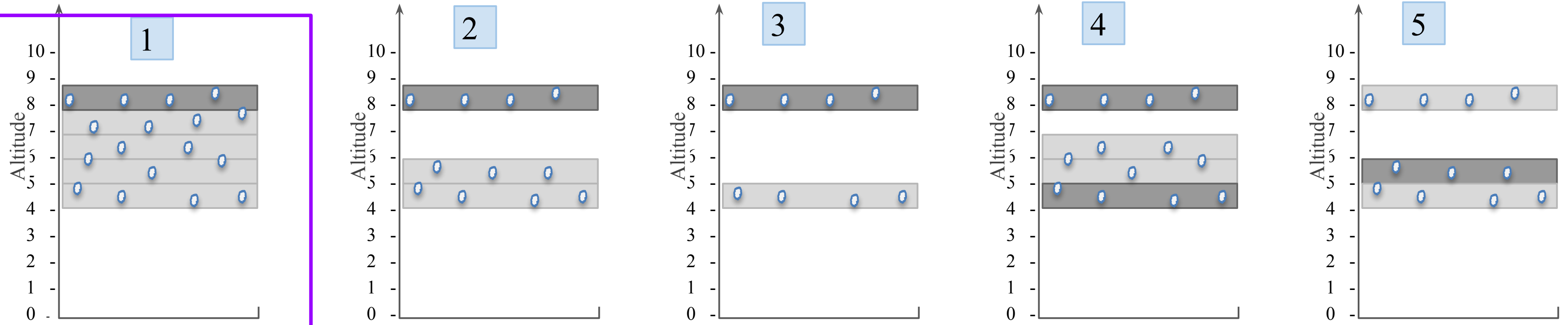




Comportement latitudinal et saisonnier de d'humidité et de températures à la surface



Method: Sensitivity of surface LW fluxes to cloud profile



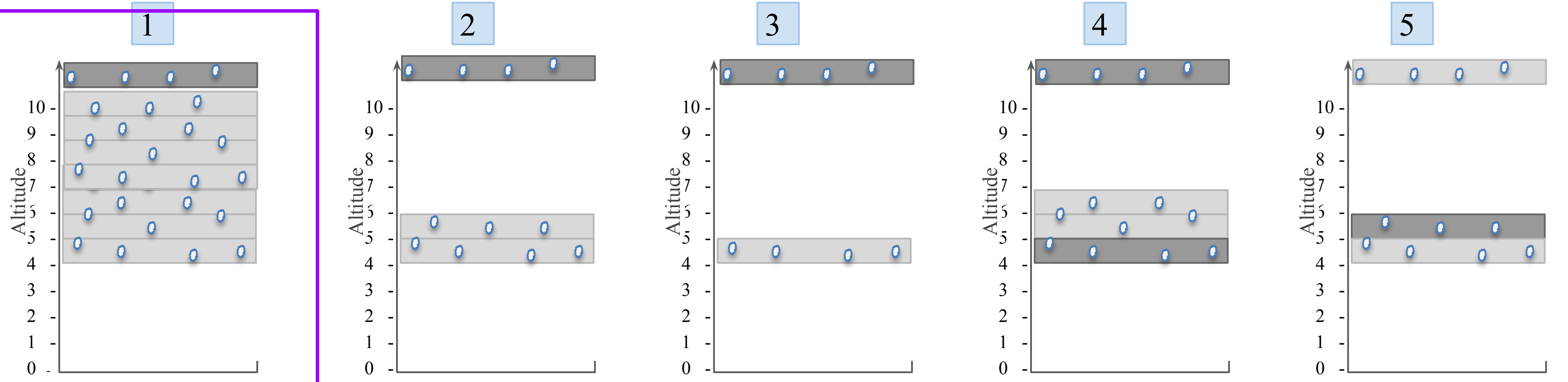
LW optical depth of the opaque cloud = 20 and the LW optical depth of thin cloud integrated over the column = to 1.6

$F^{\downarrow}_{All\text{-}Sky,\ LW}$ **= 316.1 W m^{-2}**   **= 319.9 W m^{-2}**   **= 321.9 W m^{-2}**   **= 327.7 W m^{-2}**   **= 323.4 W m^{-2}**

LW optical depth of the opaque cloud = 20 and the LW optical depth of each thin cloud layer = to 0.4

$F^{\downarrow}_{All\text{-}Sky,\ LW}$ **= 316.1 W m^{-2}**   **= 314.6 W m^{-2}**   **= 310.7 W m^{-2}**   **= 327.7 W m^{-2}**   **= 322.2 W m^{-2}**

Method: Sensitivity of surface LW fluxes to cloud profile



LW optical depth of the opaque cloud = 20 and the LW optical depth of thin cloud integrated over the column = to 1.6

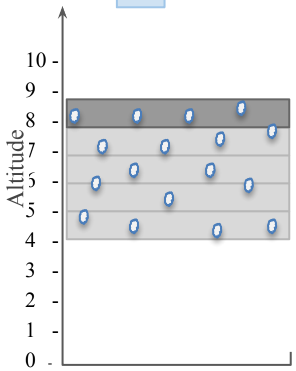
$F^{\downarrow}_{All\text{-}Sky,\ LW}$ = 313.9 W m^{-2} | = 317.8 W m^{-2} | = 319.7 W m^{-2} | = 327.7 W m^{-2} | = 323.4 W m^{-2}

LW optical depth of the opaque cloud = 20 and the LW optical depth of each thin cloud layer = to 0.4

$F^{\downarrow}_{All\text{-}Sky,\ LW}$ = 313.9 W m^{-2} | = 309.4 W m^{-2} | = 302.3 W m^{-2} | = 327.7 W m^{-2} | = 322.2 W m^{-2}

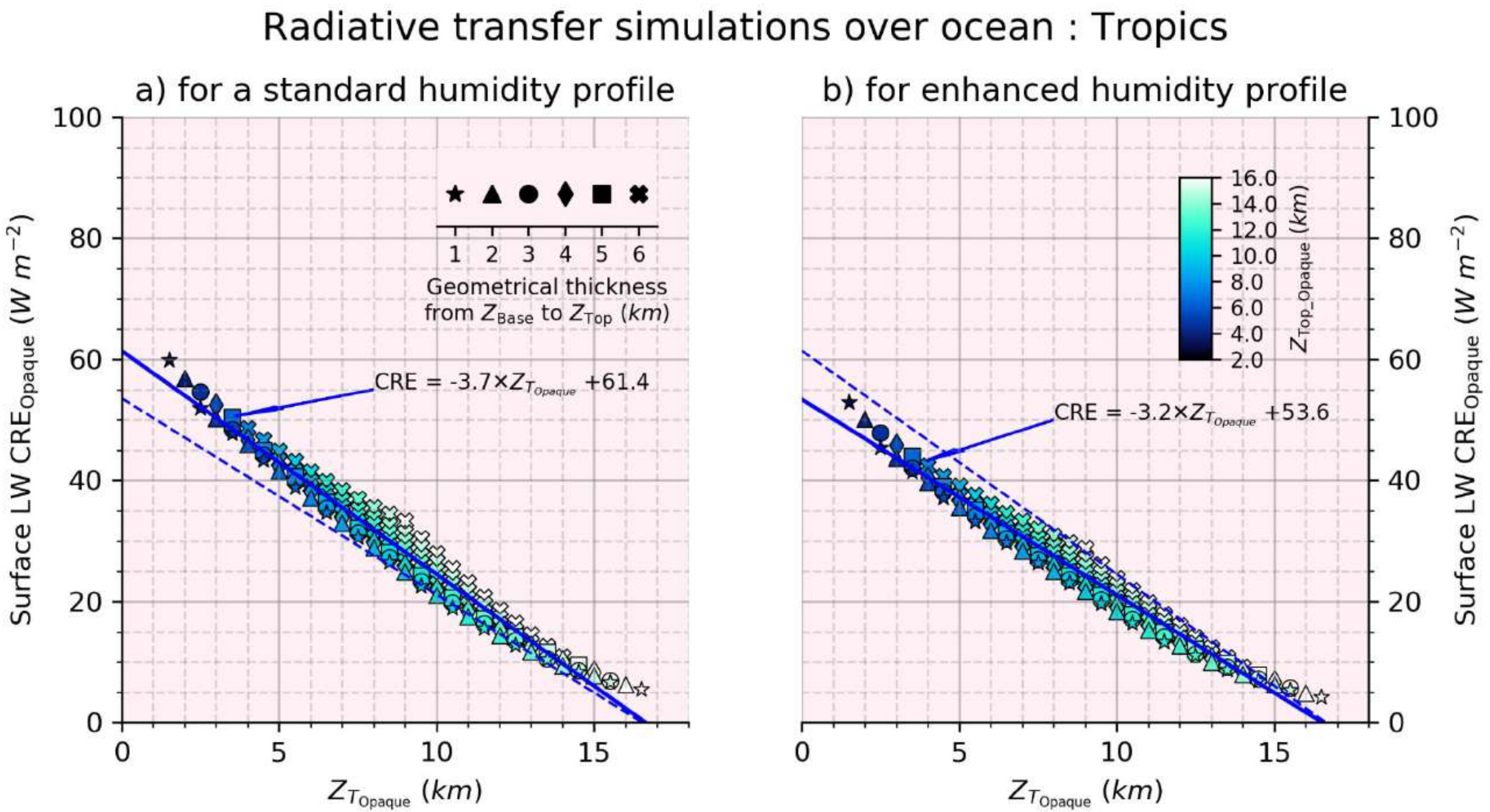
Method: Sensitivity of surface LW fluxes to particle shape

1

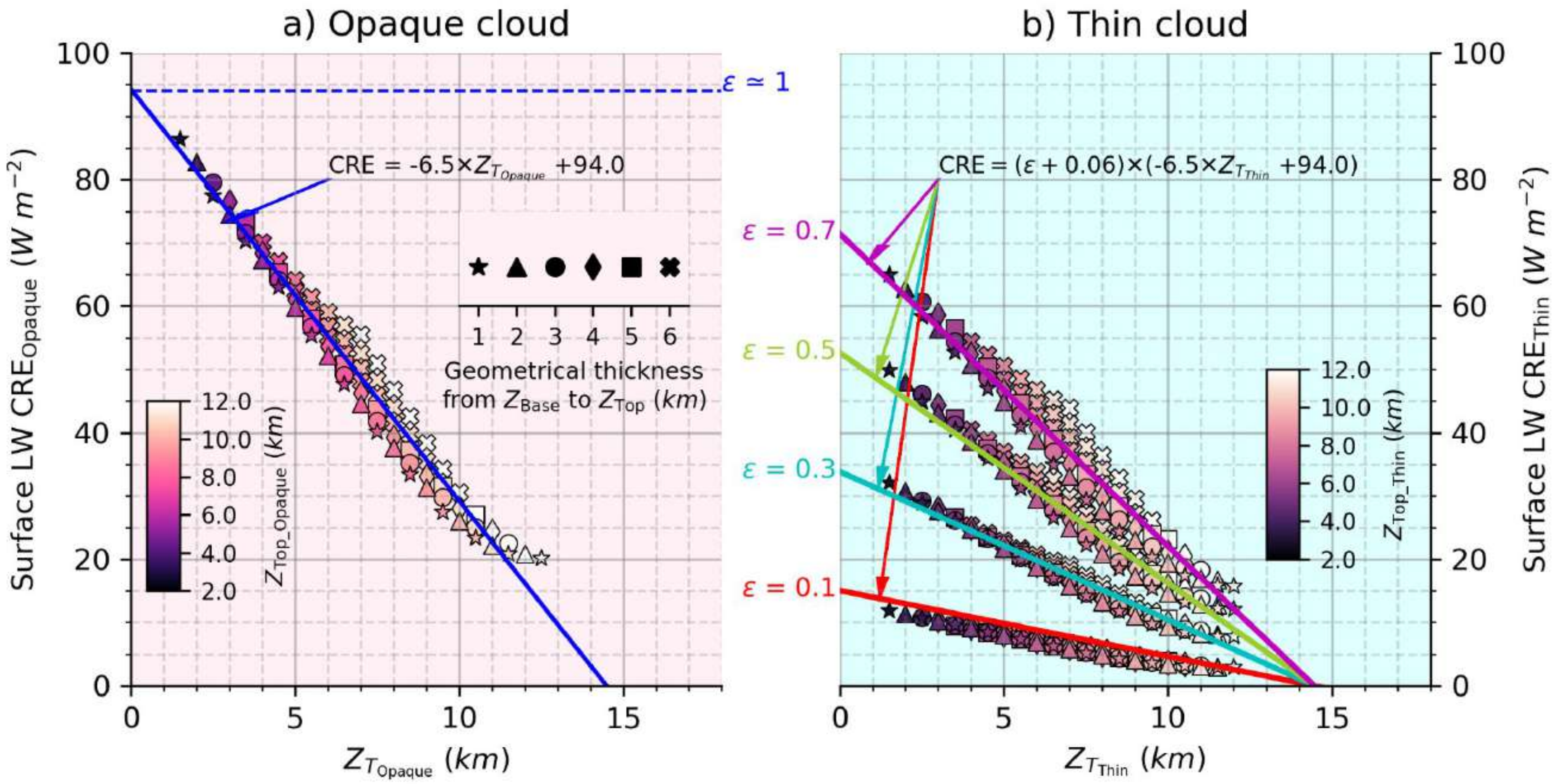


Particule type	$F^{\downarrow}_{\text{All-Sky, LW}}$
1	**= 315.0 W m^{-2}**
2	**= 315.2 W m^{-2}**
3: Spherical	**= 316.1 W m^{-2}**
4	**= 315.4 W m^{-2}**
5	**= 315.1 W m^{-2}**
6	**= 315.9 W m^{-2}**
7	**= 316.4 W m^{-2}**

Sensitivity to humidity profiles



Radiative transfer simulations over land



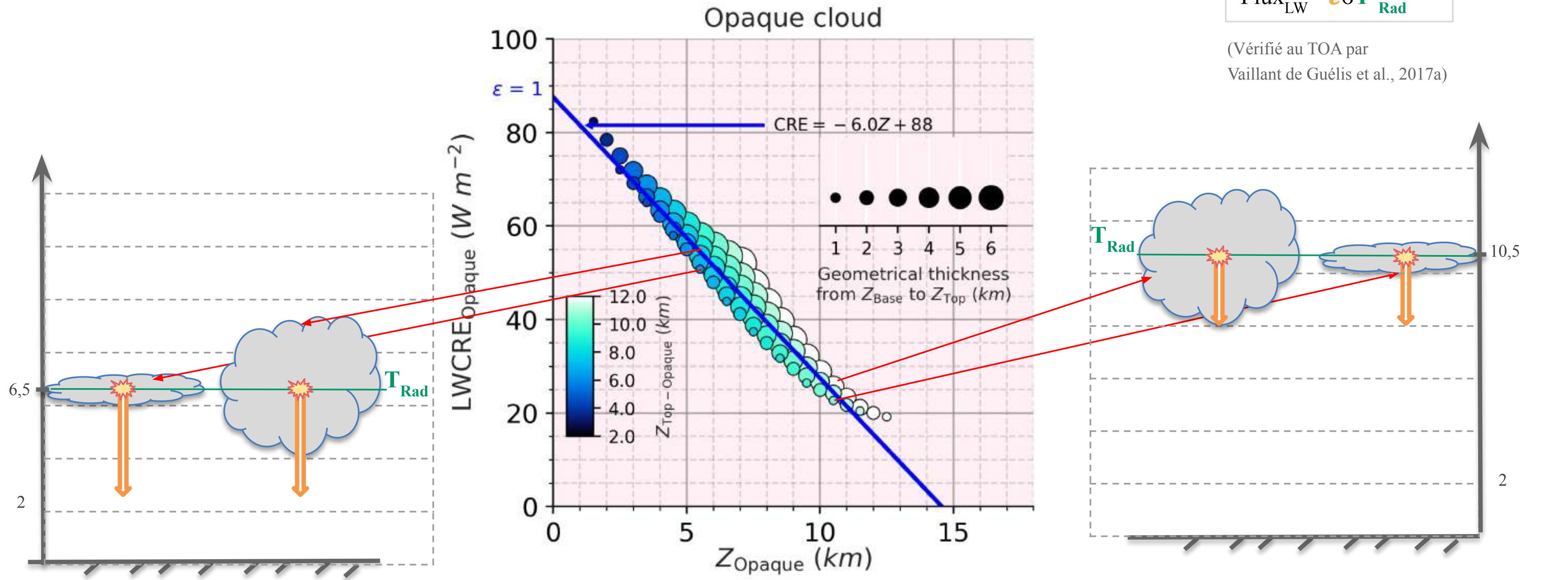
Radiative transfer simulations: Trad

Radiative transfer simulations over oceans : Month01_Lat+39

(Dubuisson et al., 2004)

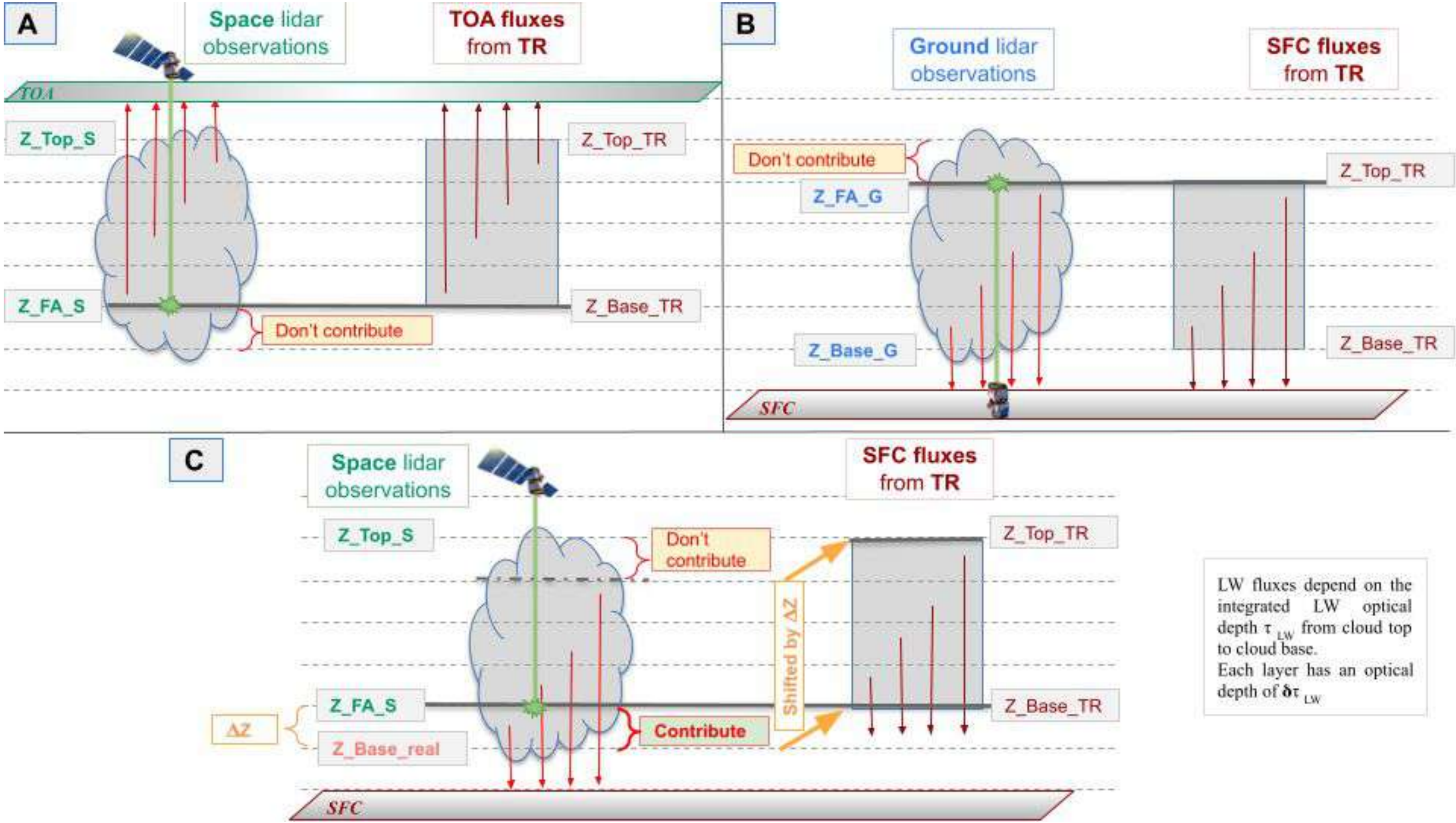
$$Flux_{LW} = \varepsilon \sigma T^4_{Rad}$$

(Vérifié au TOA par
Vaillant de Guélis et al., 2017a)



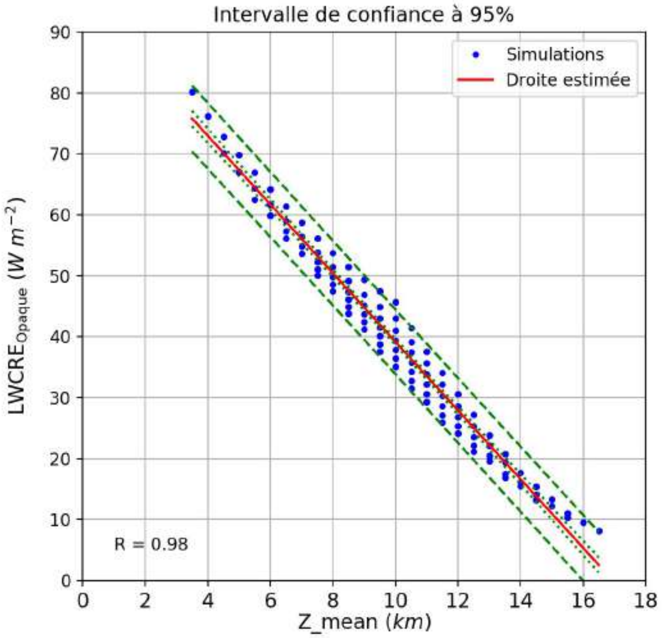
$$CRE_{LW} = [Flux_{All\_Sky} - Flux_{Clear-Sky}]_{LW}$$

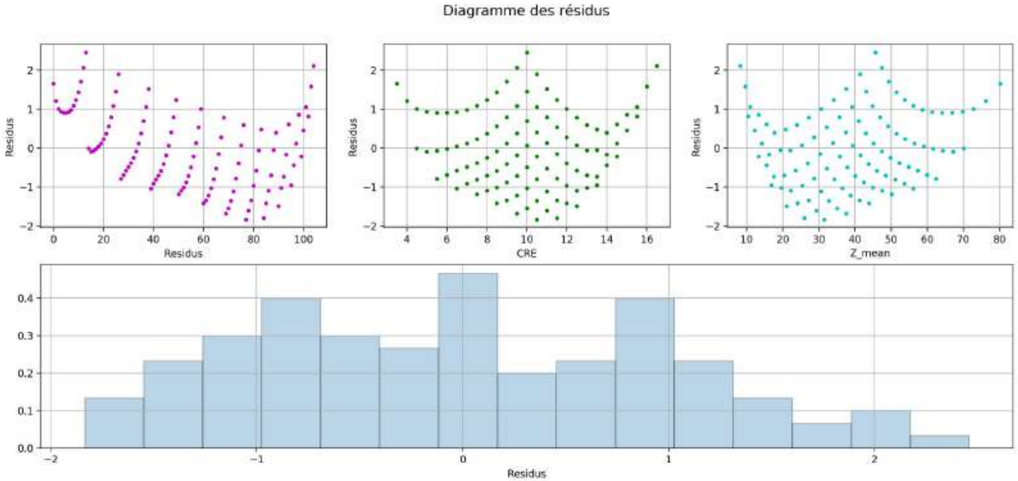
Issue: the space lidar doesn't observe the opaque cloud base altitude



LW fluxes depend on the integrated LW optical depth τ_{LW} from cloud top to cloud base.
Each layer has an optical depth of $\delta\tau_{LW}$

Radiative transfer simulations: Linear regression



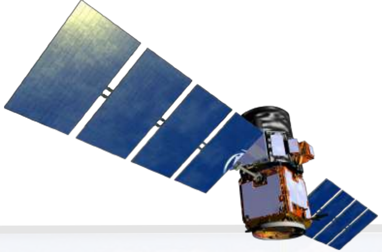


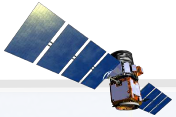
$$CRE_{Opaque} = -\,5.635 \times Z_{Opaque} + 95.517$$

b (=95.517) ∈ [93.696 ; 97.338]
a (=-5.635) ∈ [-5.810 ; -5.460].

- errors in global cloud-forcing estimates are extremely difficult to assess because of the need to account for uncertainties in clear-sky radiative fluxes, to represent errors in the specification of cloud properties, and to distinguish random errors from systematic errors (**HENDERSON et al 2013)**

```
month01_lat+39_Ocean_thin4_6_thick8          Nom de ce fichier (pour GAME_paral)
"/homedata/aarouf/GAME_PhD/atm_prof_Ocean/1990_2017_month01_lat+39_Ocean_prof"
Profil atmosphérique (avec chemin et "")
50.0 2000.0             Limites spectrales w1, w2 (en cm-1)
0.02 282.2 .TRUE.            Albedo de Surface, Température de surface, Diffusion multiple
3             Nombre de nuages
4 3 13 0.400            numero couche nuage, type nuage, index taille effective, cot @ 12mc
5 3 13 0.400            numero couche nuage, type nuage, index taille effective, cot @ 12mc
8 3 13 1000.000         numero couche nuage, type nuage, index taille effective, cot @ 12mc
8             NSTR
0             UMU0
```





Surface longwave cloud radiative effect derived from space lidar observations: application in the Arctic

Annex LWCRE–LIDAR

April 21st, 2023: PhD defense

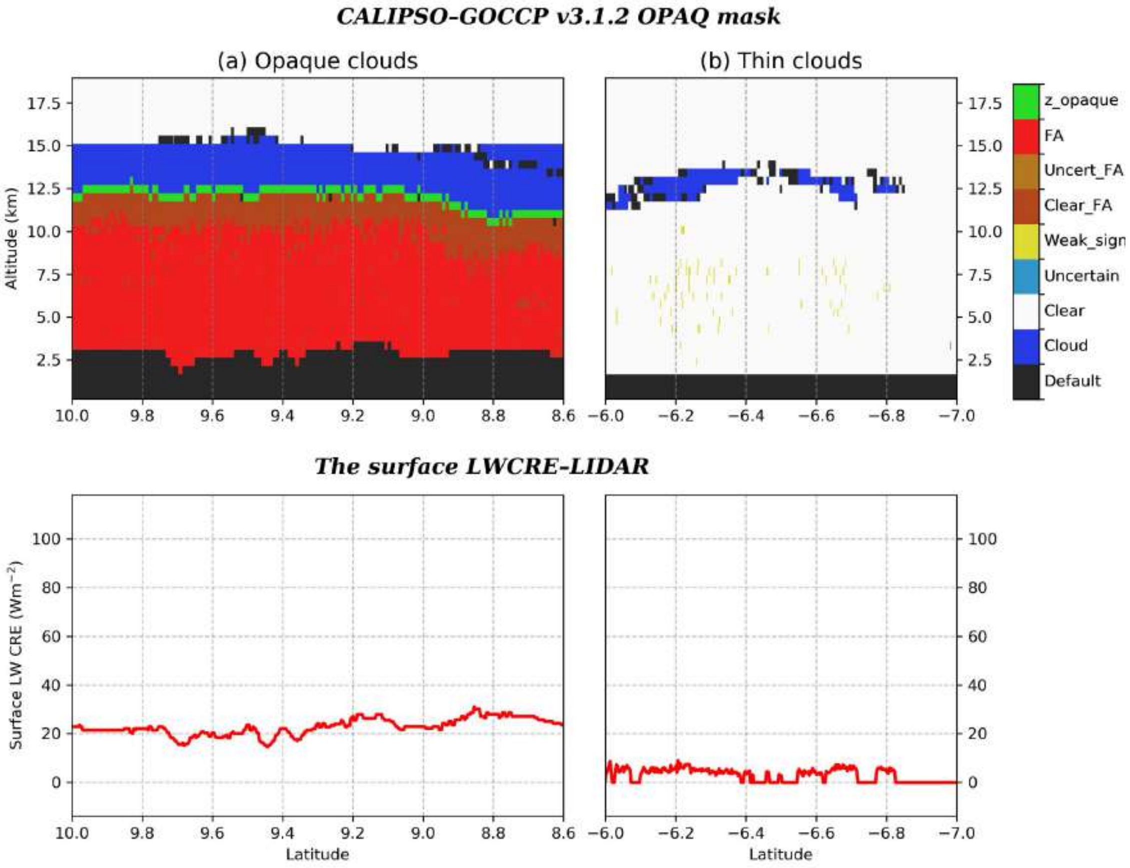
Assia Arouf

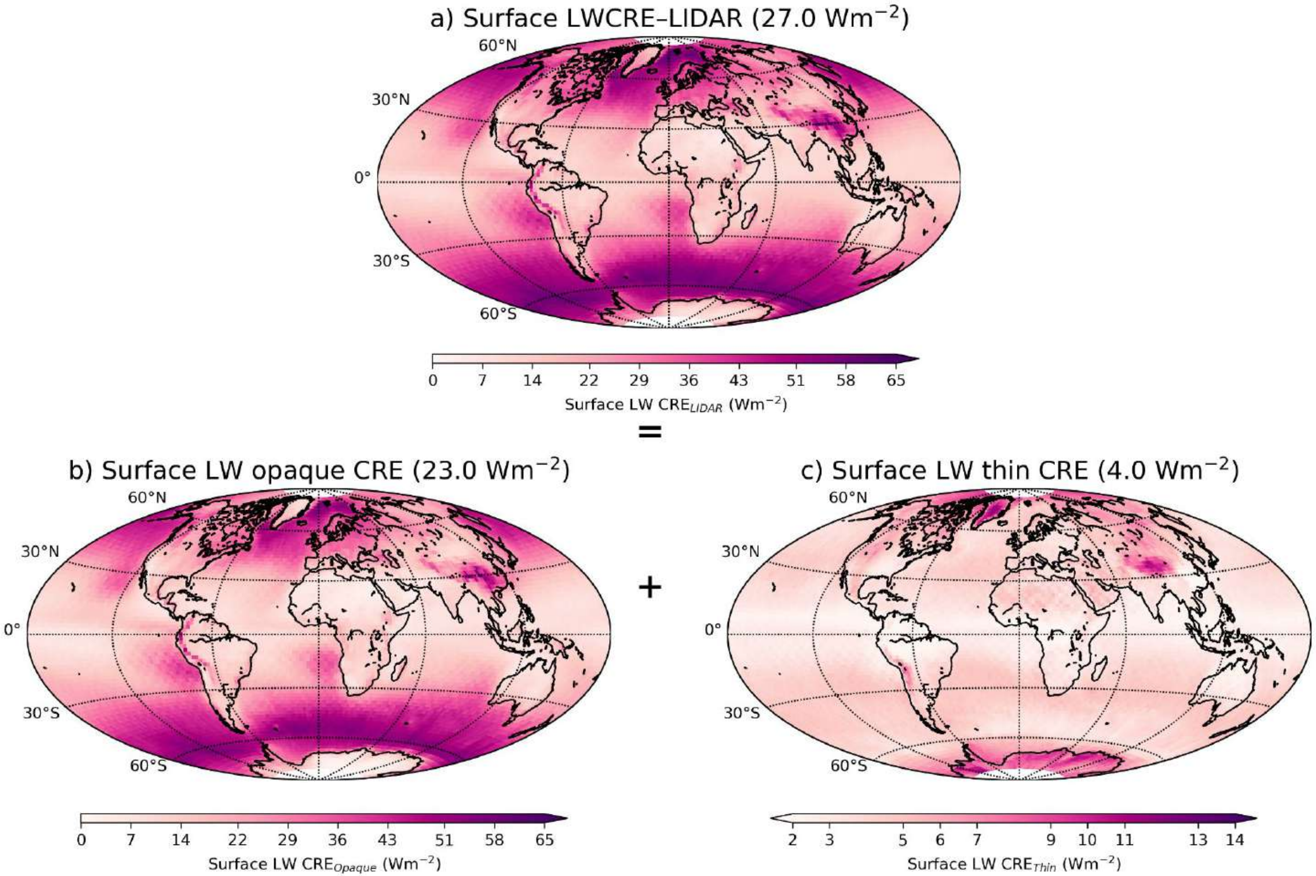
Supervisor: Hélène Chepfer

SORBONNE UNIVERSITÉ

l'X ÉCOLE POLYTECHNIQUE

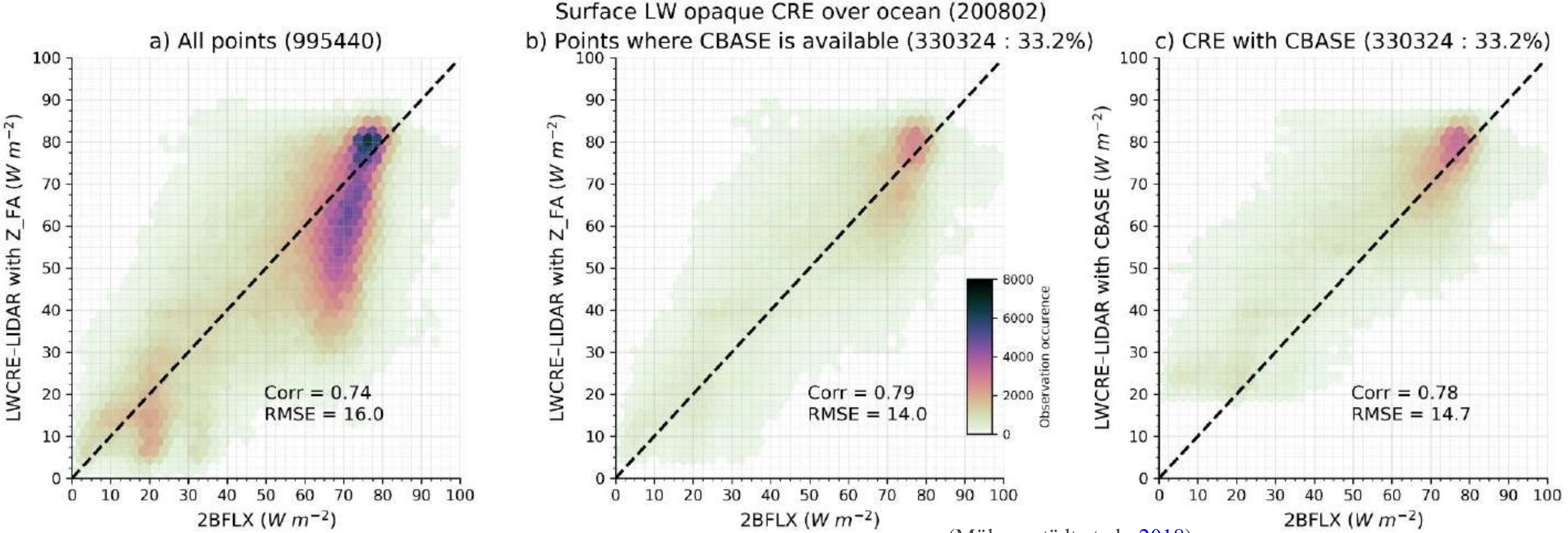
IPSL


CALIPSO-GOCCP v3.1.2 OPAQ mask
(a) Opaque clouds
(b) Thin clouds
Altitude (km)
z_opaque
FA
Uncert_FA
Clear_FA
Weak_sign
Uncertain
Clear
Cloud
Default
The surface LWCRE-LIDAR
Surface LW CRE (Wm⁻²)
Latitude
Latitude


a) Surface LWCRE–LIDAR (27.0 Wm^{-2})
60°N
30°N
0°
30°S
60°S
0 7 14 22 29 36 43 51 58 65
Surface LW CRE$_{LIDAR}$ (Wm^{-2})
=
b) Surface LW opaque CRE (23.0 Wm^{-2})
0 7 14 22 29 36 43 51 58 65
Surface LW CRE$_{Opaque}$ (Wm^{-2})
+
c) Surface LW thin CRE (4.0 Wm^{-2})
2 3 5 6 7 9 10 11 13 14
Surface LW CRE$_{Thin}$ (Wm^{-2})

Validation Méthode

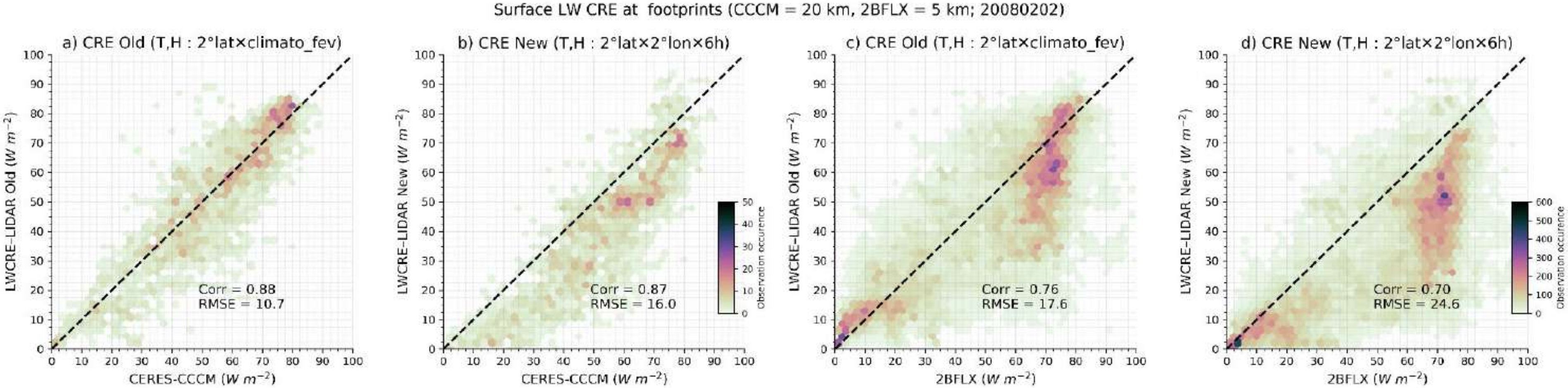
Using a better representation of cloud base from spaceborne lidar



(Mülmenstädt et al., 2018)

- *Using a more advanced cloud base in the LWCRE–LIDAR algorithm will increase the surface LW CRE value retrieved in some opaque cloud profiles slightly, but it does not fundamentally change the results.*

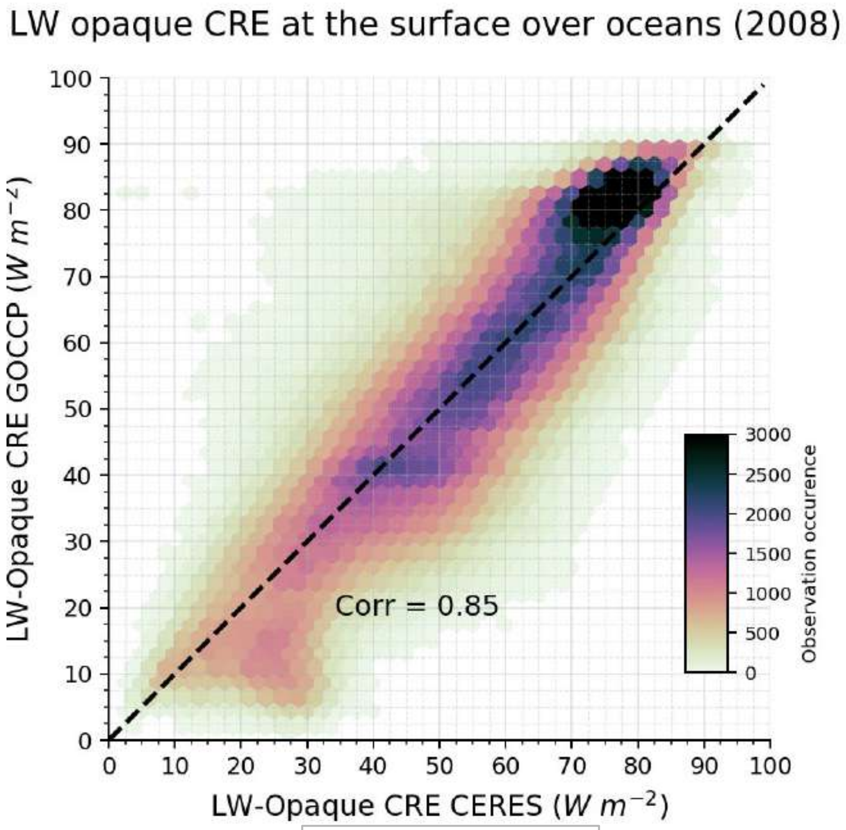
Using sub-daily humidity and temperature profiles



- *Sub-daily profiles in LWCRE–LIDAR retrieval makes the comparison to other satellite products worse at footprint scale.*
- *This suggests that the differences between the three daily products are likely due to other causes than LWCRE–LIDAR using monthly mean temperature/humidity profiles.*

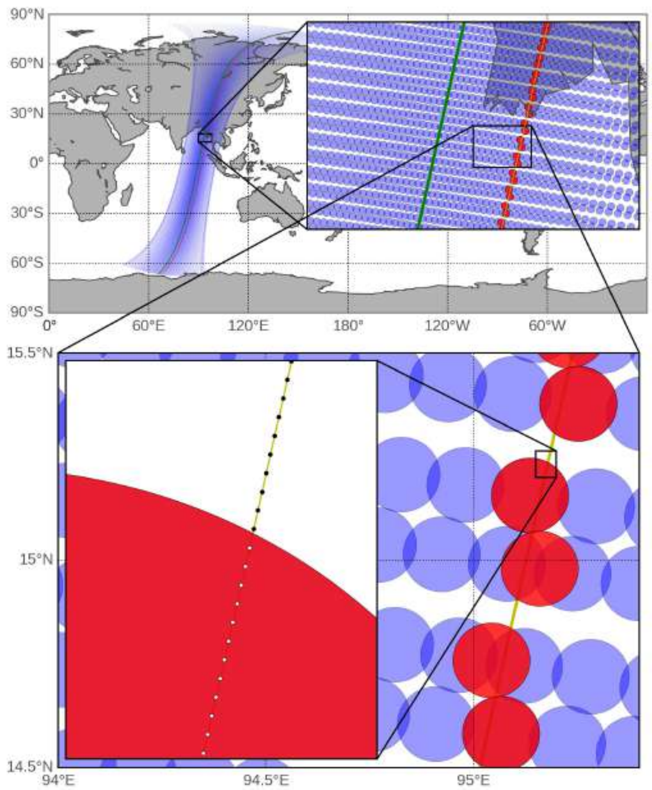
Comparaison avec d'autres produits spatiaux : données instantanées colocalisées

CRE lidar



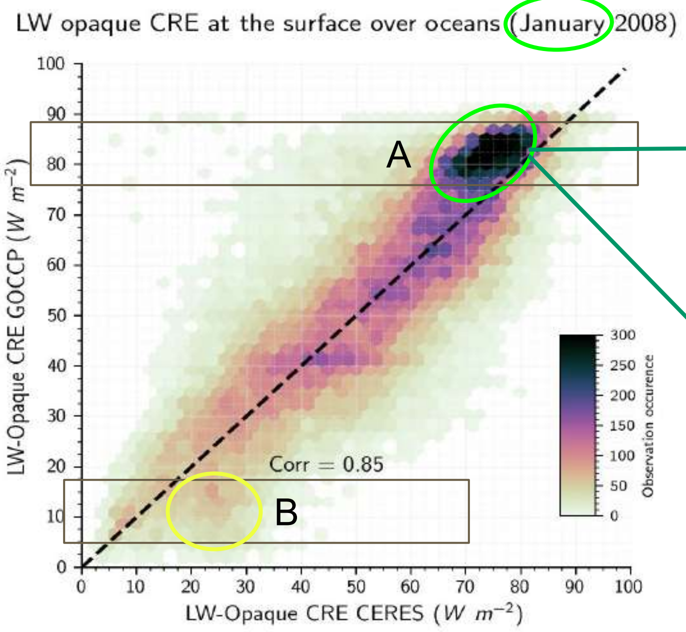
CRE radiomètre

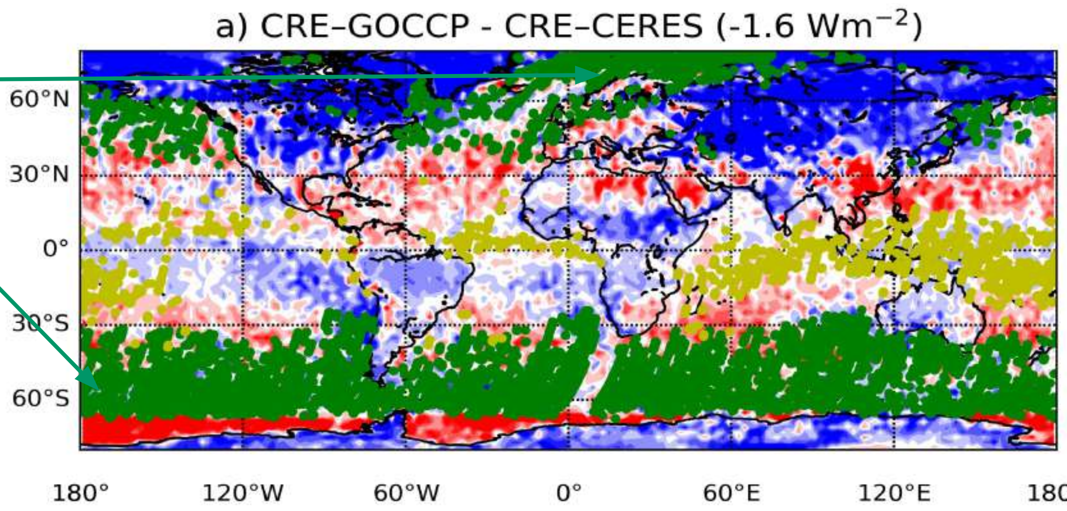
CERES
(Kato et al., 2018)

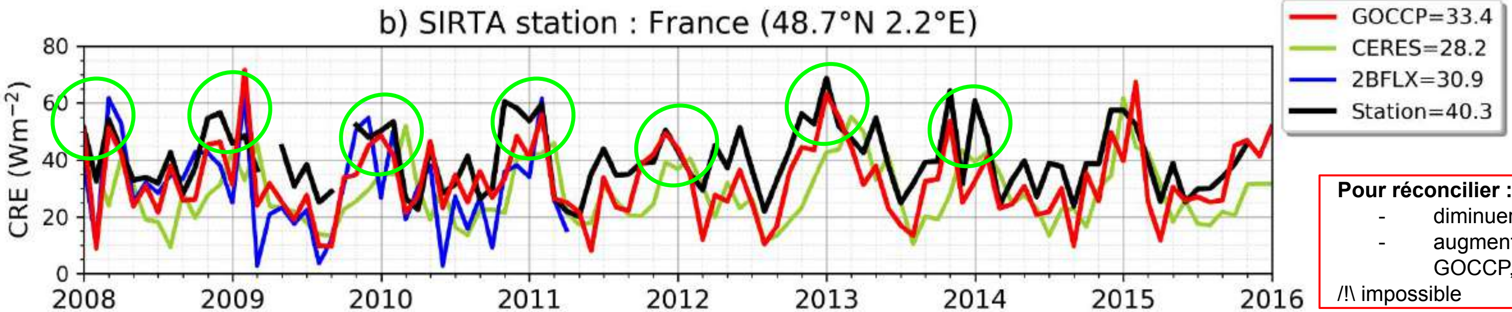


(Vaillant de Guélis 2018)

Analyse des CRE colocalisés : paquet A







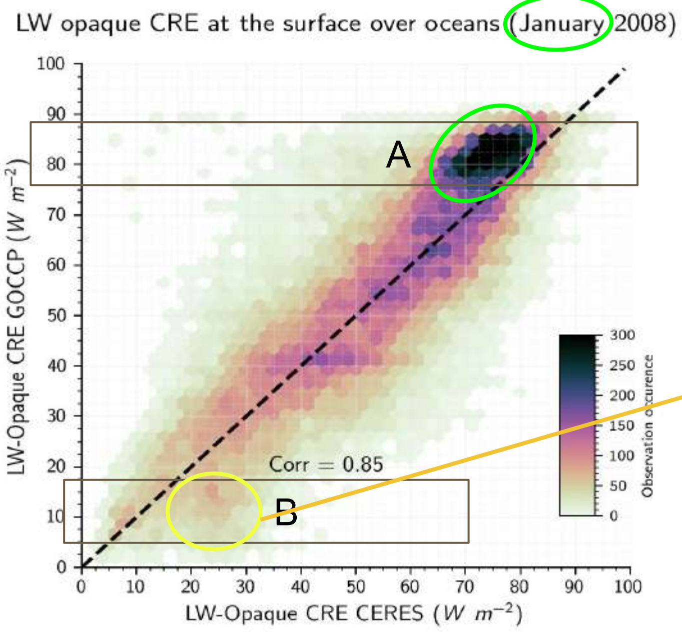
Le CRE GOCCP est supérieur au CRE CERES dans les MidLat. En comparant à la station sol des Midlat pour les mois de janvier, Le CRE GOCCP est proche des mesures sols et sont plus large que le CRE CERES de 20 W/m2

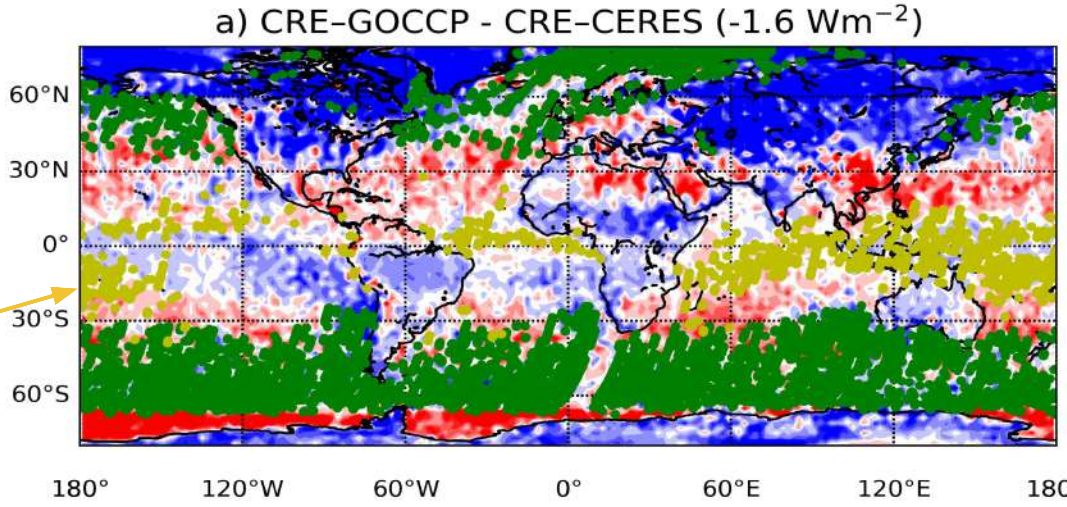
Pour réconcilier :

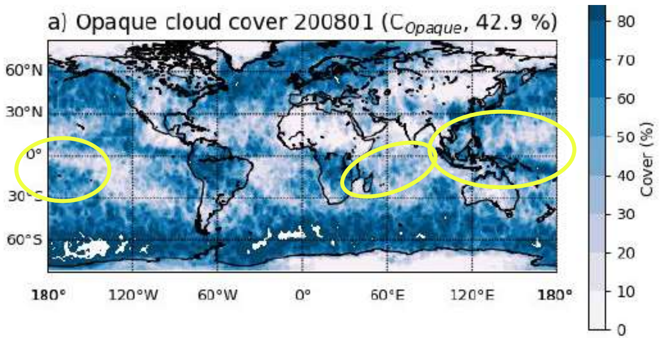
- diminuer la couverture GOCCP
- augmenter l'altitude des nuages GOCCP,

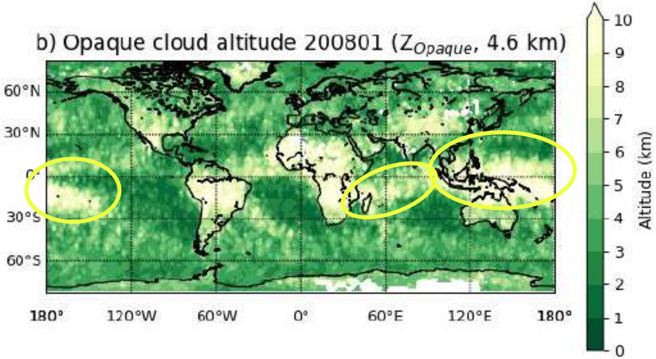
/!\ impossible

Analyse des CRE colocalisés : paquet B





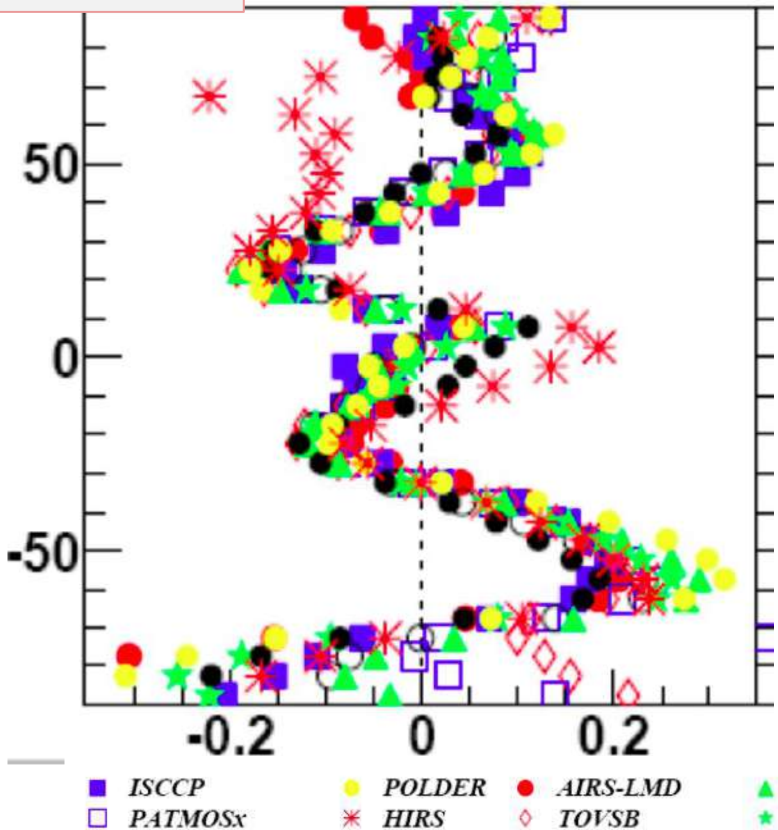




Le CRE GOCCP est inférieur au CRE CERES dans les Tropiques le long de l'ITCZ et dans la warmpool. dans ces régions la couverture opaque est large(40-60%) et les nuages sont à de hautes altitudes (8_10 km). le signal lidar va être atténuer rapidement dans le nuage et ne verra pas la base/(majorité) du nuage.

MODIS over detect clouds in polar regions : GEWEX Cloud Assessment

GEWEX CA (2012)



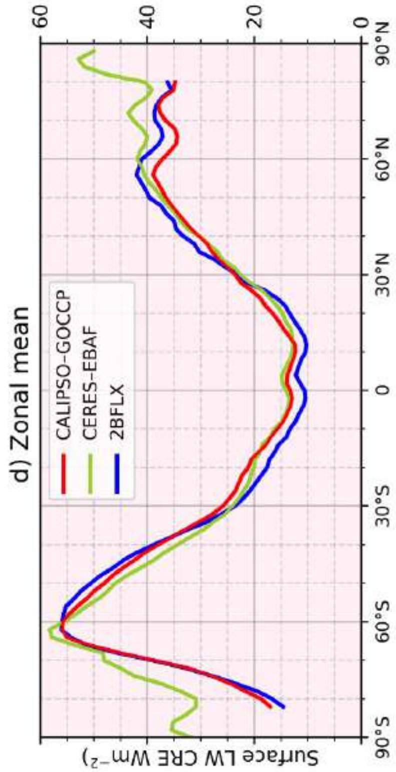
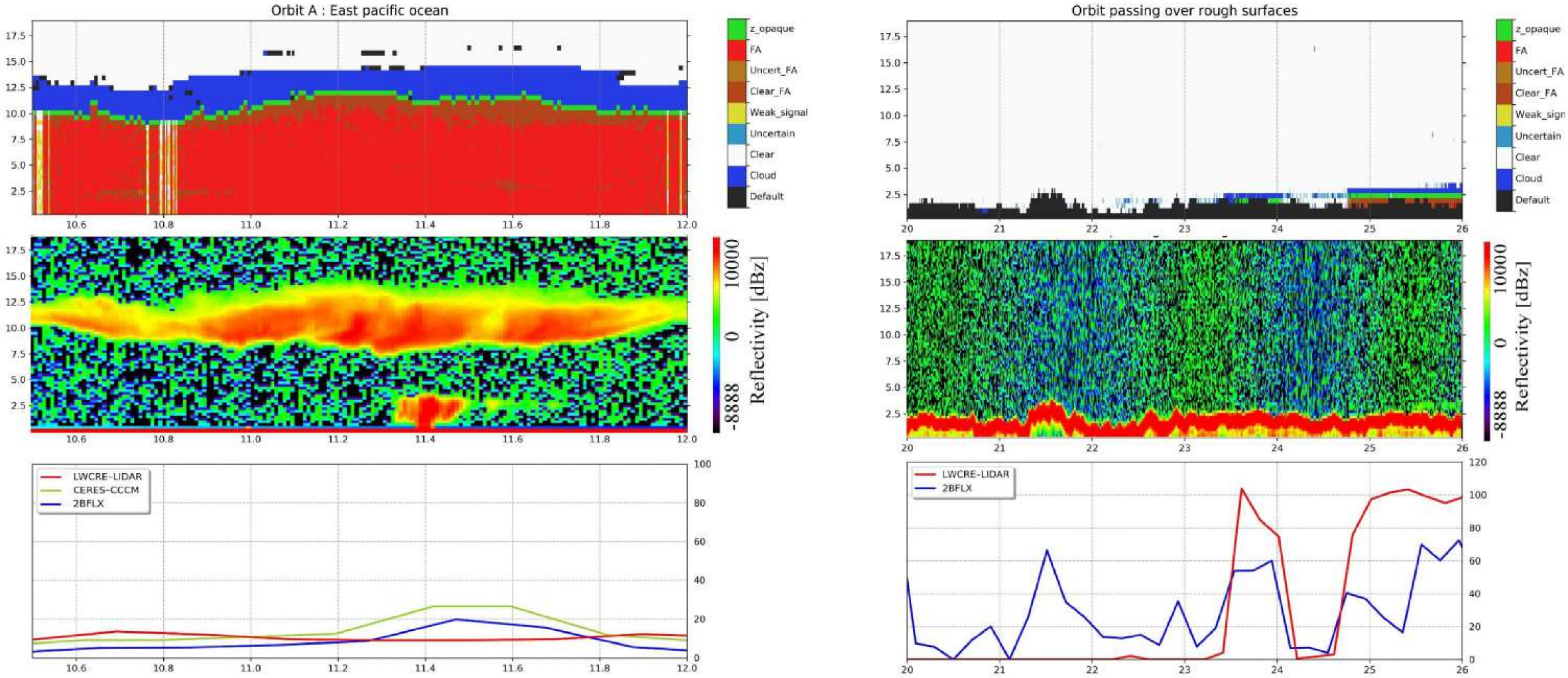
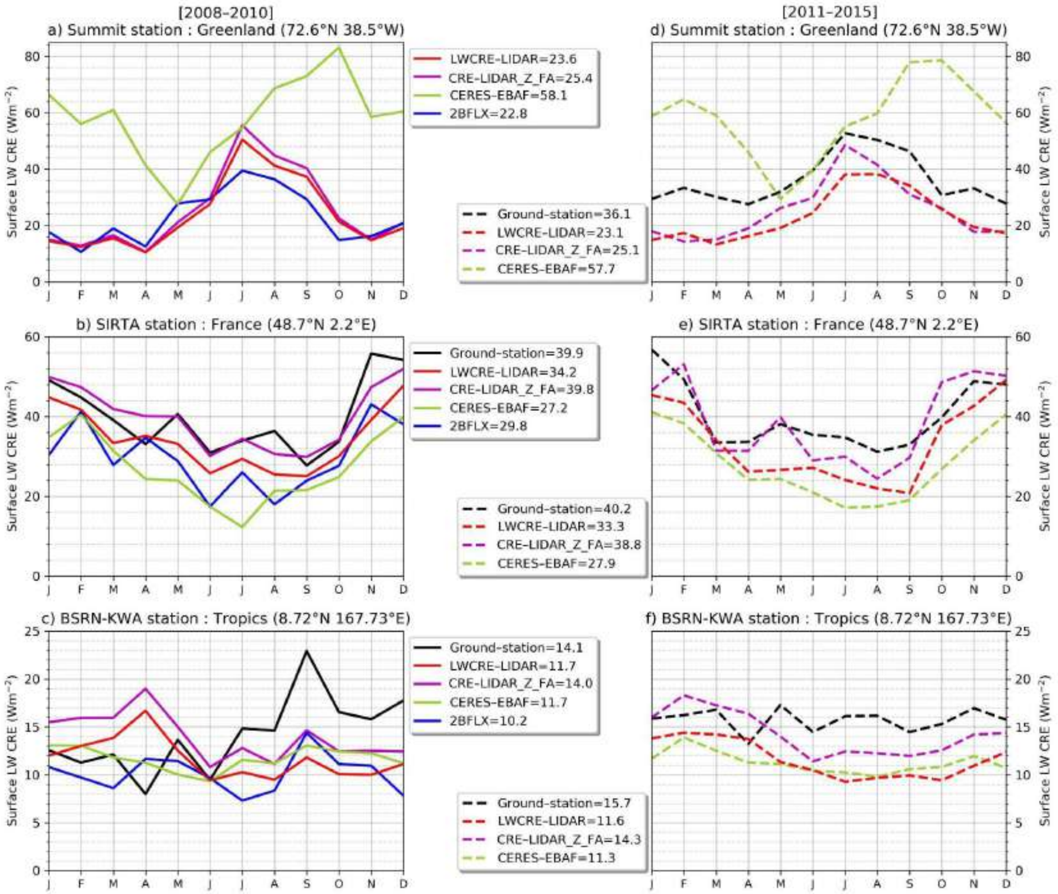


Figure 3.1.6: Latitudinal variation of annual mean cloud amount CA, effective cloud amount CAE, cloud emissivity CEM and cloud temperature CT, as well as of their height-stratified averages (relative to CA), presented as differences between latitudinal averages and global mean. Statistics at 1:30 PM LT (3:00 PM for ISCCP).

CALIPSO–GOCCP–OPAQ mask and CloudSat CPR reflectivity



Comparison to ground stations: space lidar doesn't observe opaque cloud base altitude



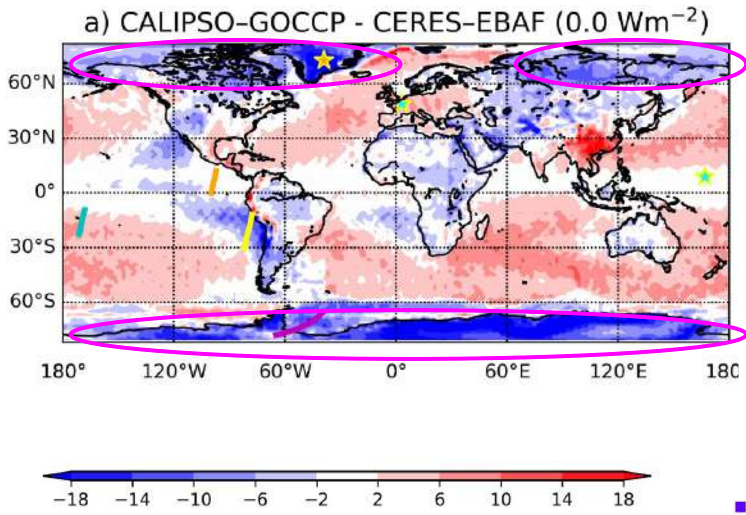
1) Use the lowest altitude Z_FA of the observable opaque clouds:
   a) by definition, Z_FA < Z_T_Opaque
   b) => T_FA > T_Opaque
   c) => CRE_Z_FA > CRE_Z_T_Opaque
2) Slightly reduces the differences with respect to the ground stations
   a) => the fact of not seeing the cloud base has an impact on the CRE LW at the surface
3) Increases the differences with other space products but reduces the differences with ground stations
   a) => there are other sources of uncertainties (which may also be present in other space products)

The added value of surface LWCRE–LIDAR compared to CERES–EBAF

1) Better restitution over icy surfaces (Fig.a) where CERES–EBAF relies on MODIS to detect clouds

   /!\ MODIS detects more clouds than other sensors in polar regions (GEWEX CA, Fig.2)

2) Better seasonal cycle over icy surfaces => could have a significant impact on climate related processes, such as cryosphere melting (Fig. d).



GEWEX CA. (2012)

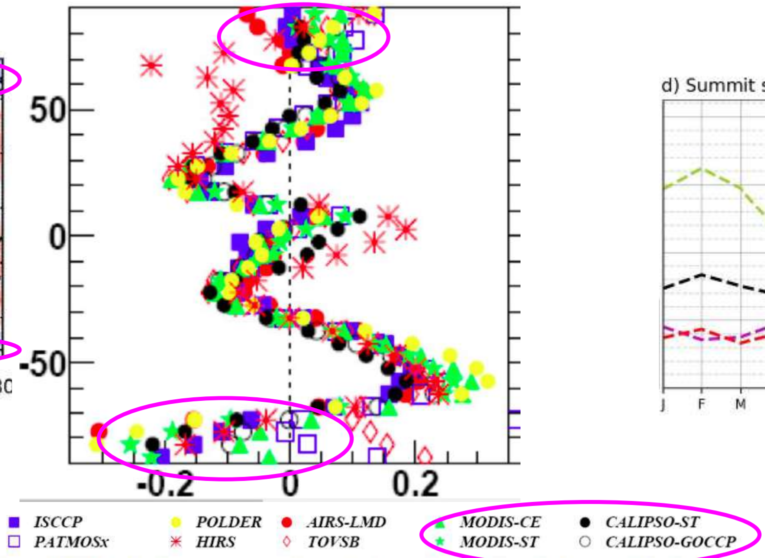
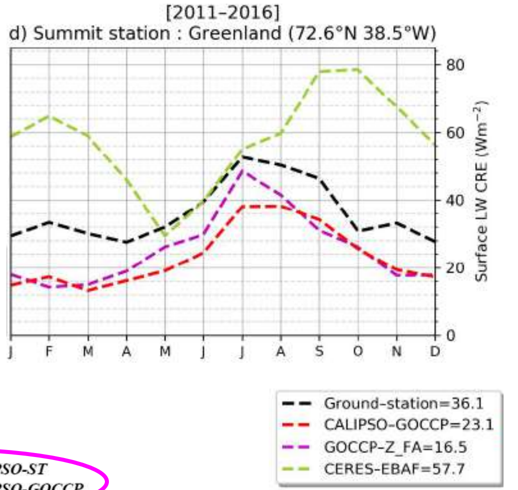
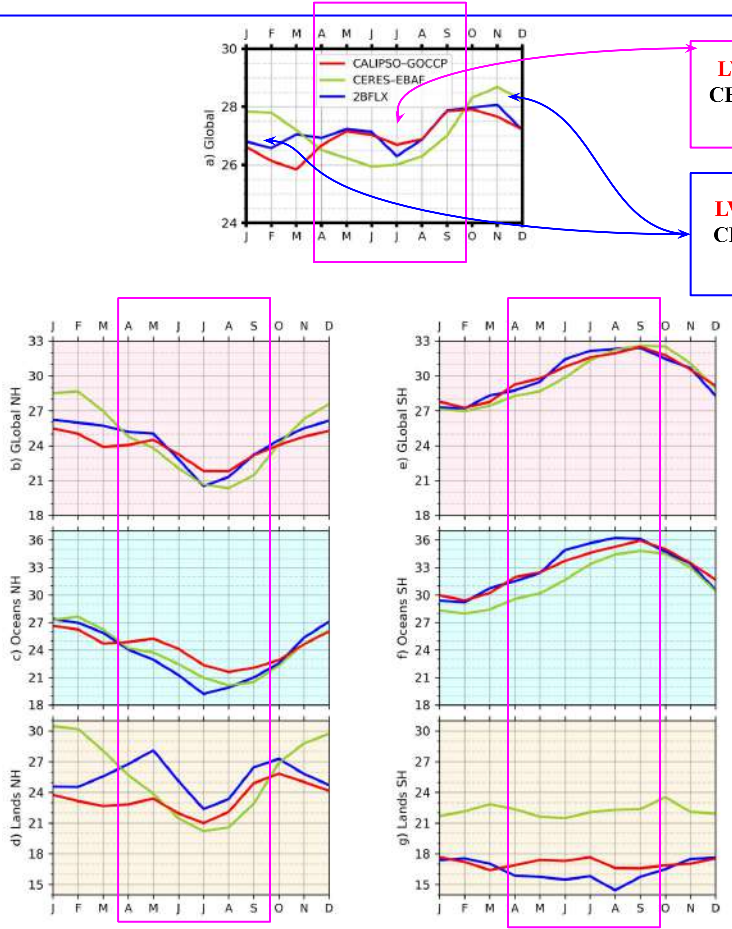


Figure 3.1.6: Latitudinal variation of annual mean cloud amount CA, effective cloud amount CAE, cloud emissivity CEM and cloud temperature CT, as well as of their height-stratified averages (relative to CA), presented as differences between latitudinal averages and global mean. Statistics at 1:30 PM LT (3:00 PM for ISCCP).



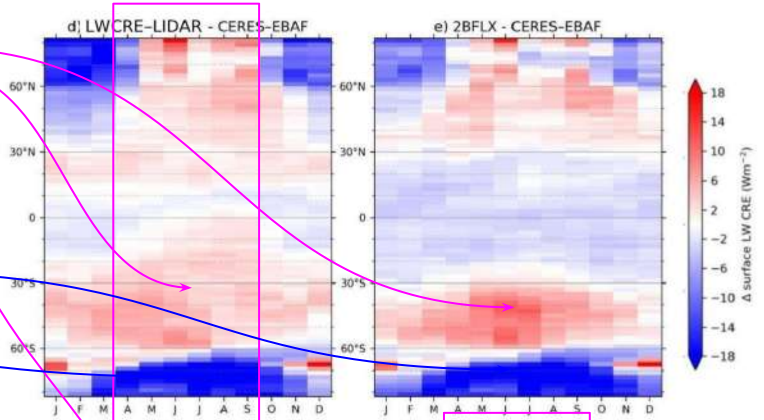
The added value of surface LWCRE–LIDAR compared to CERES–EBAF

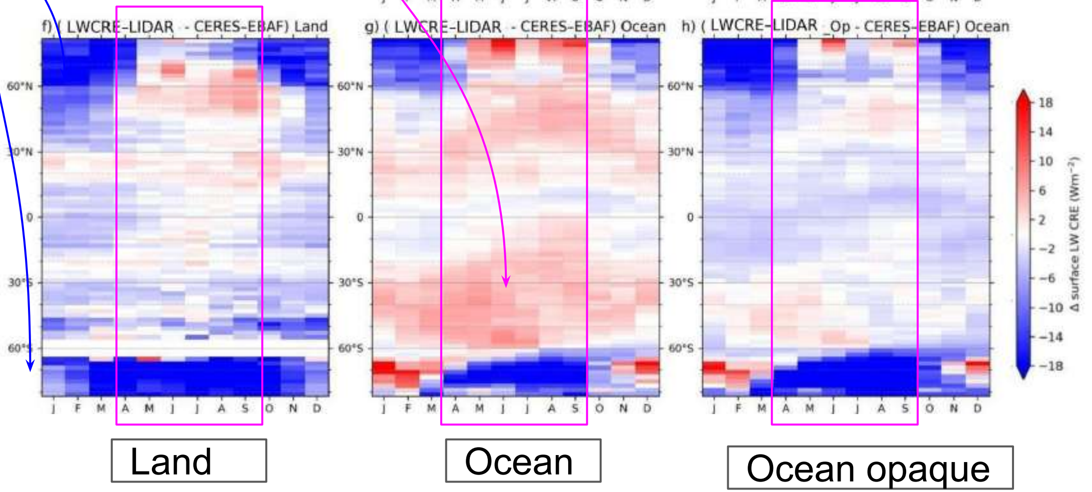


LWCRE–LIDAR > CERES-EBAF
CERES doesn't see low thin cloud in the boundary layer.

LWCRE–LIDAR < CERES-EBAF
CERES over detects clouds over icy surfaces.

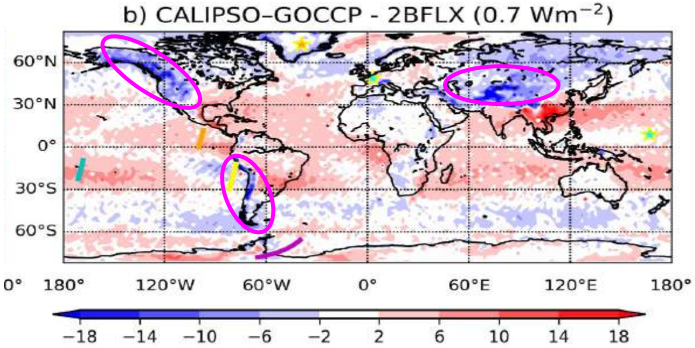
(GEWEX CA, 2012)

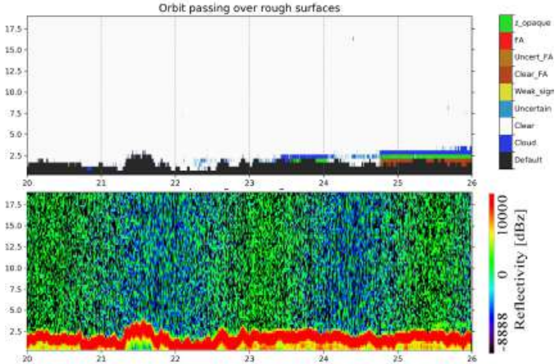


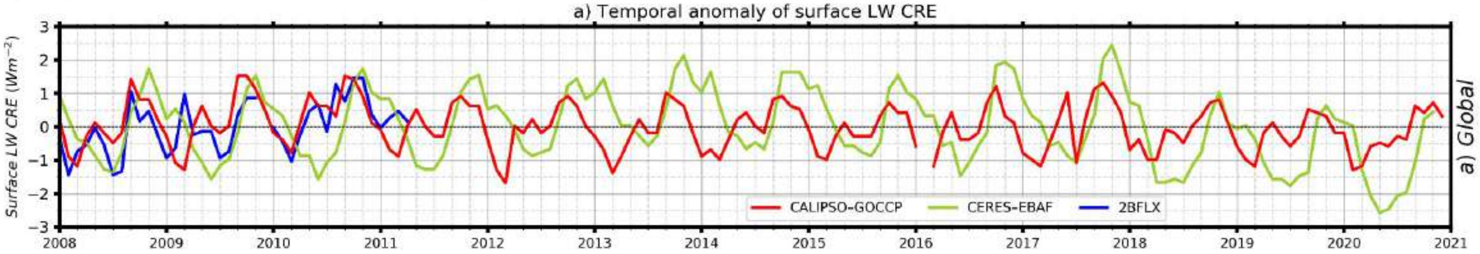


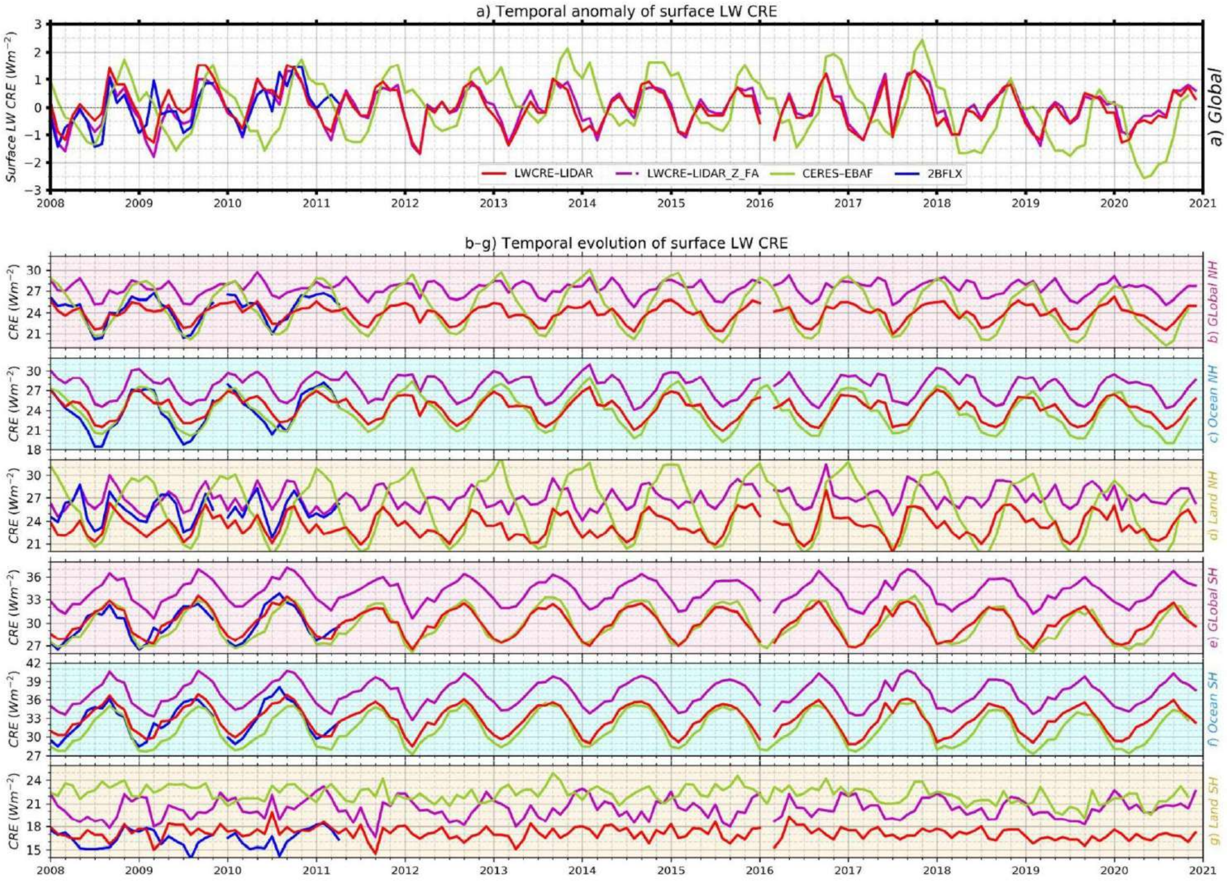
The added value of surface LWCRE–LIDAR compared to 2BFLXHR–LIDAR

1) Better restitution over surfaces with strong orography (F.1) where the radar is polluted by the surface echo (F.2)
   a) Detects more clouds where there are none
2) A longer time series (15 years Vs 5 years) (Fig. 3)
   a) => Possibility to study a 2016 El-Nino event.
   b) => Possibility to study variations of the CPR and the cloud properties driving it and their trends.
3) "CloudSat CPR's long powerful pulse also generates a surface clutter echo which tends to partially mask signals from cloud and precipitation forming below circa 1 km (Marchand et al., 2008)"

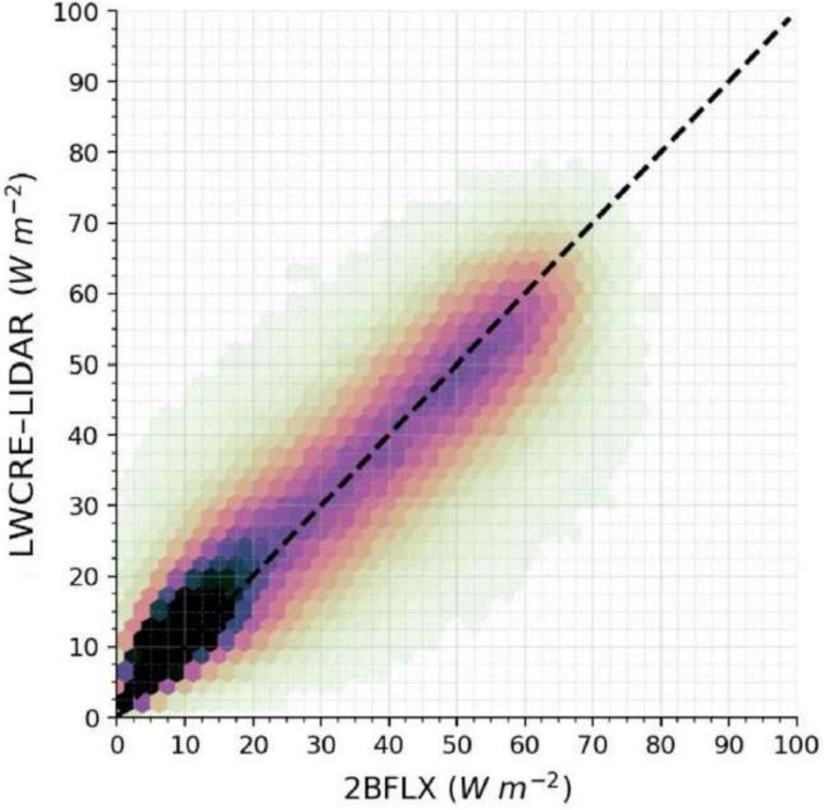






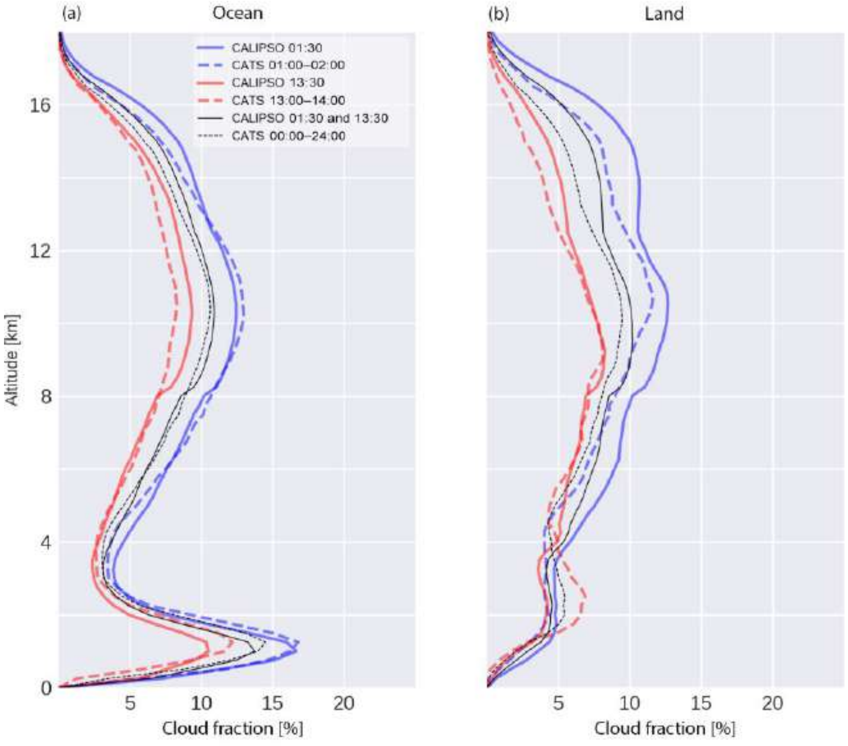

a) Temporal anomaly of surface LW CRE
Surface LW CRE (Wm^{-2})
a) Global
LWCRE-LIDAR
LWCRE-LIDAR_Z_FA
CERES-EBAF
2BFLX
b-g) Temporal evolution of surface LW CRE
CRE (Wm^{-2})
b) GLobal NH
c) Ocean NH
d) Land NH
e) GLobal SH
f) Ocean SH
g) Land SH

Surface LW CRE from gridded products (2008–2010)

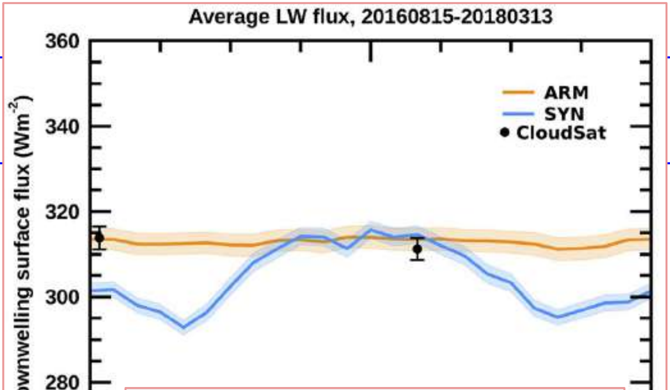


Diurnal cycle of clouds

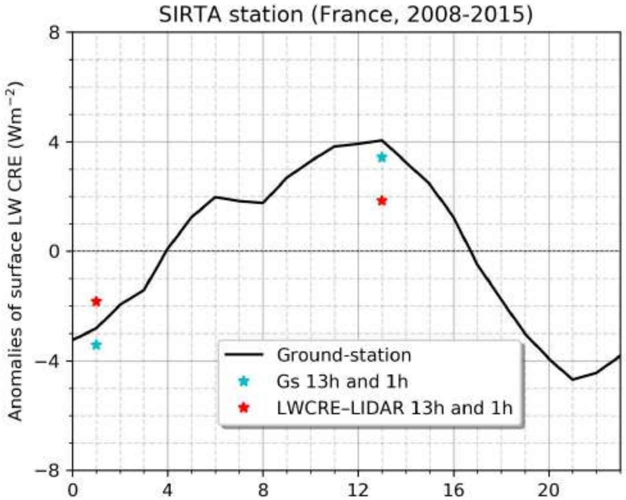
.: Diurnal cycle of vertical cloud profiles from space lidar



From Noel et al. (2017)

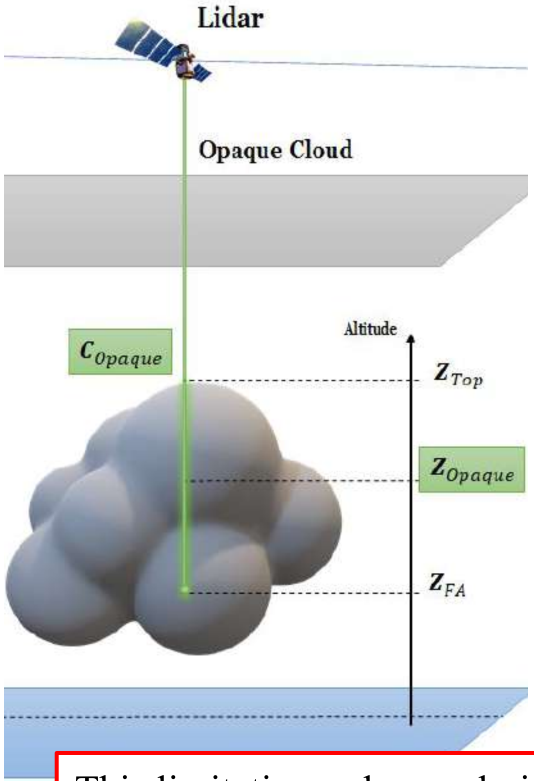


Hinkelman and Marchand (2020)



		2008/01-2011/04 periode			2008-2015 periode	
		LWCRE–LIDAR	LWCRE–LIDAR_Z_FA	2BFLX	LWCRE–LIDAR	LWCRE–LIDAR_Z_FA
Greenland	Bias	-8.5	-7.9	-16.4	-13.6	-11.6
	RMSE	9.0	8.4	16.9	15.9	15.0
	Correlation	0.91	0.95	0.45	0.69	0.70
SIRTA	Bias	-5.7	-0.1	-9.9	-6.6	-0.8
	RMSE	11.0	10.4	15.5	10.8	9.5
	Correlation	0.73	0.73	0.67	0.77	0.77
KWA	Bias	-2.3	-0.3	-4.1	-3.4	-0.9
	RMSE	6.1	5.6	6.9	5.7	4.9
	Correlation	0.03	0.15	0.23	0.08	0.21

Issue: the space lidar doesn't observe the opaque cloud base altitude



We used Z_{FA} to retrieve the surface LW cloud radiative effect instead of Z_{Opaque} and that increased the differences with ground stations and other space products in the wrong way.

In the tropics in deep convective regions

$Z_{FA} \gg Z_{Base\text{-}REAL}$

To reconcile : Use Z_{FA} and not Z_{Opaque} ??

$Z_{FA} < Z_{Opaque}$

$T(Z_{FA}) > T(Z_{Opaque})$

$CRE(Z_{FA}) > CRE(Z_{Opaque})$

but !!

$CRE_{GOCCP}(Z_{Opaque}) > CRE_{CERES}$ (Kato et al., 2018)

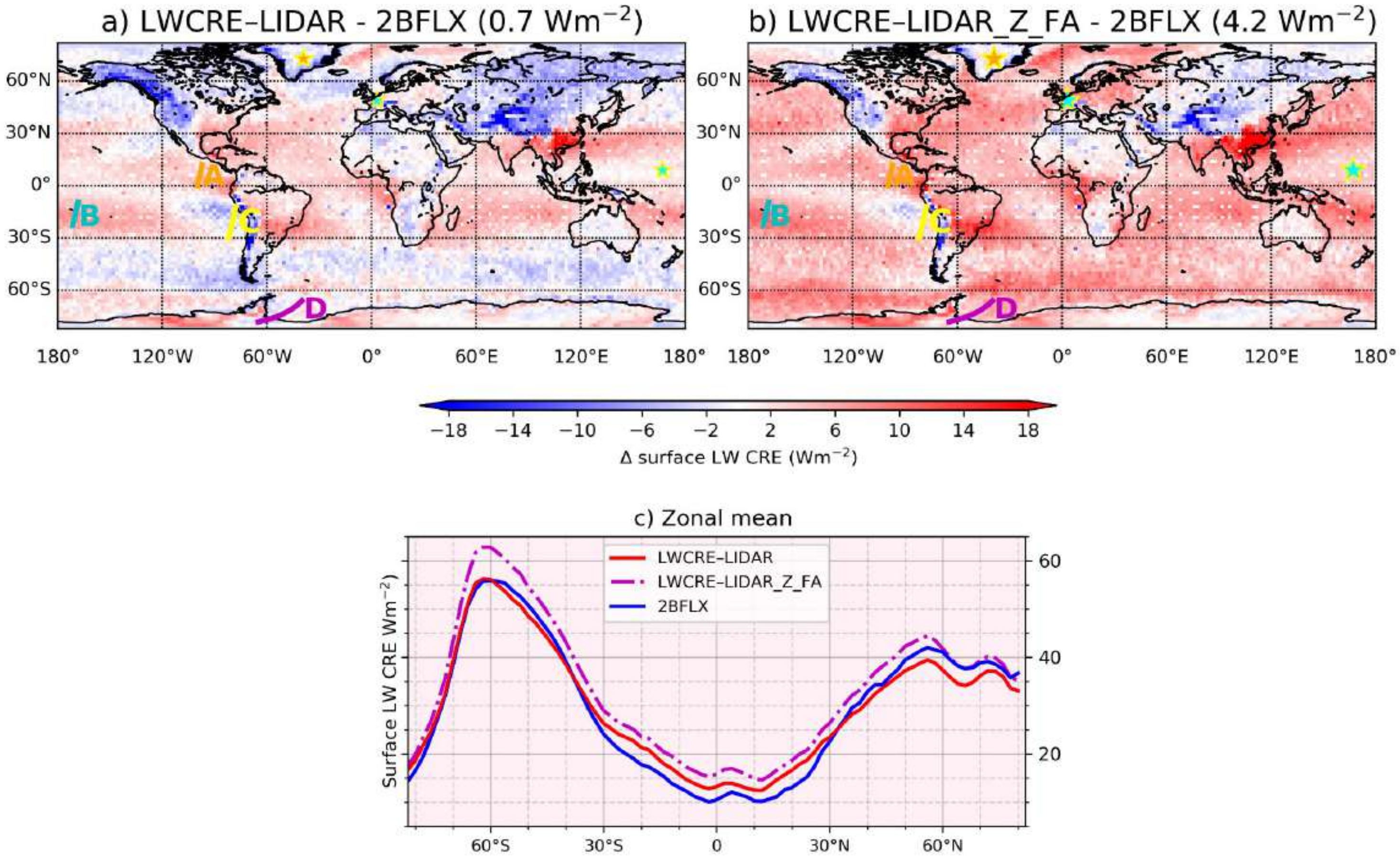
$> CRE_{2BFLX}$ (L'Ecuyer et al., 2019)

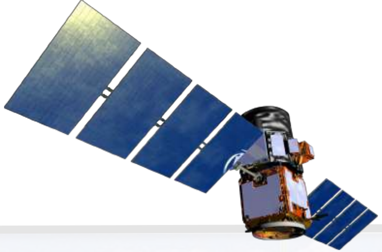
$> CRE_{KWA}$ (Roesch et al., 2011)

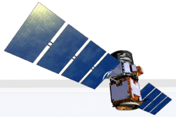
In addition, the lidar is fully attenuated at an altitude lower than 3 km above the surface most of the time (Guzman et al. 2017) except in deep convective regions.

This limitation only poorly influences the surface LW cloud radiative effect retrieval most likely in the tropics along the ITCZ and the warm-pool (10 to 15 Wm^{-2} compared to CERES).

Issue: the space lidar doesn't observe the opaque cloud base altitude







Surface longwave cloud radiative effect derived from space lidar observations: application in the Arctic

Annex Influence on sea ice loss

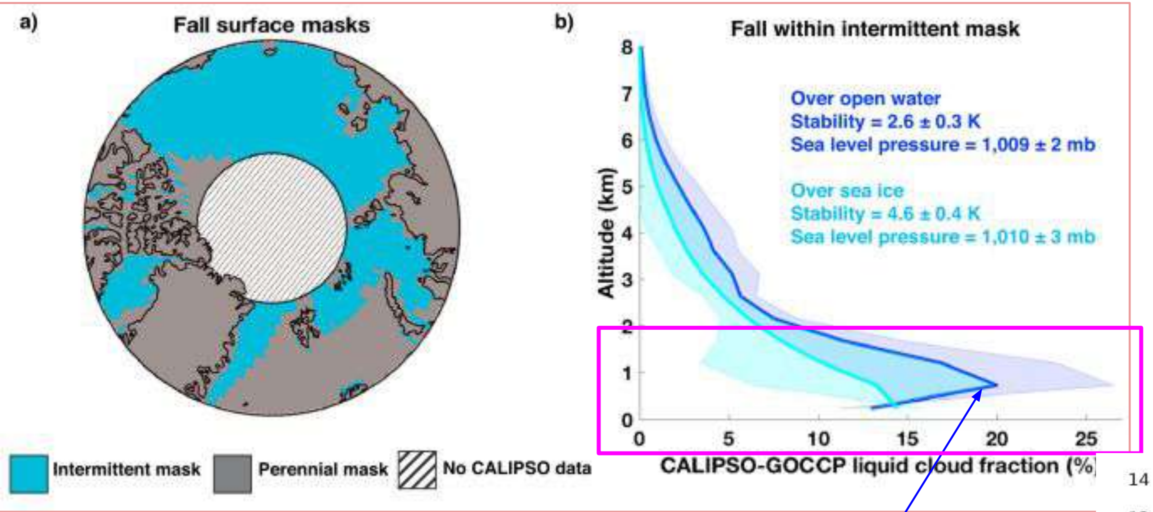
April 21st, 2023: PhD defense

Assia Arouf

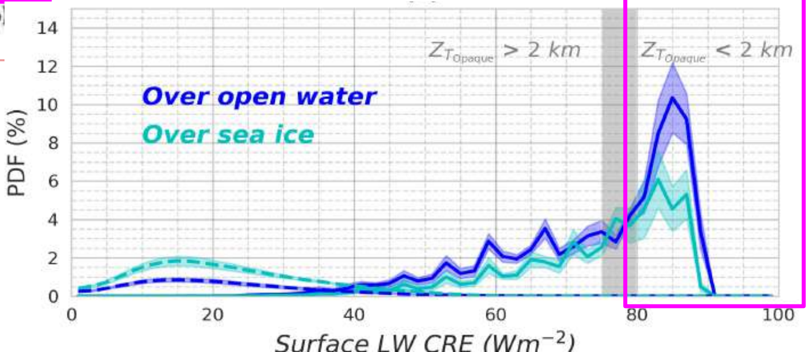
Supervisor: Hélène Chepfer

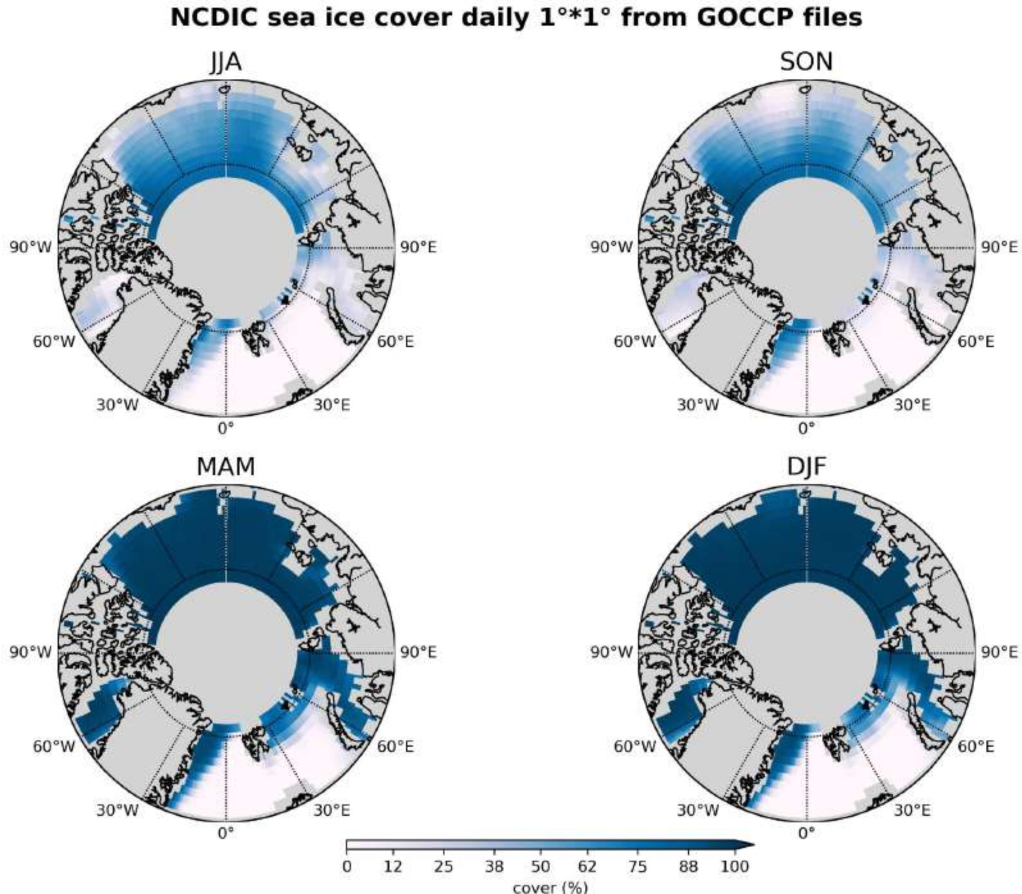
Split clouds into low-level clouds (< 2 km) and high-level clouds (> 2 km)

From Morrison et al. (2018)

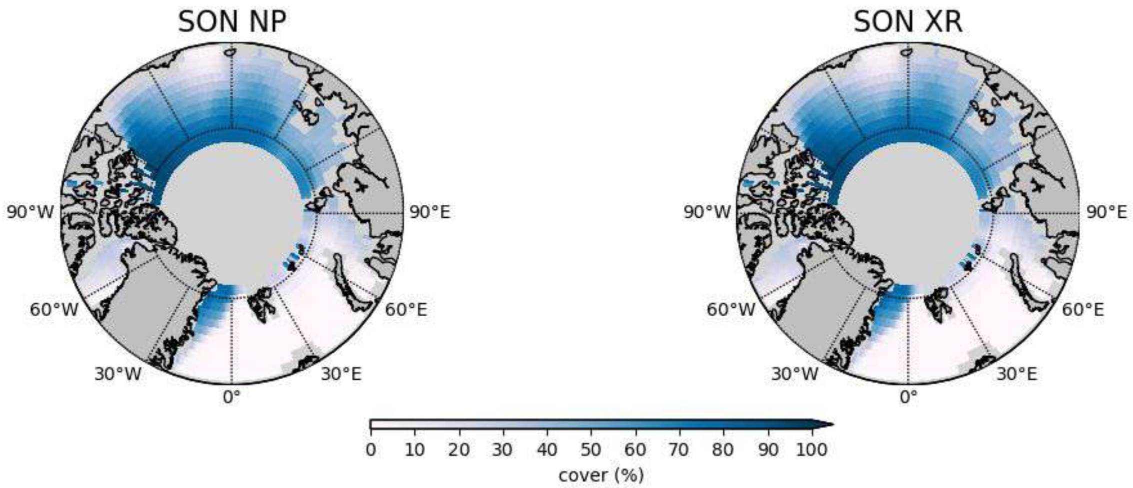


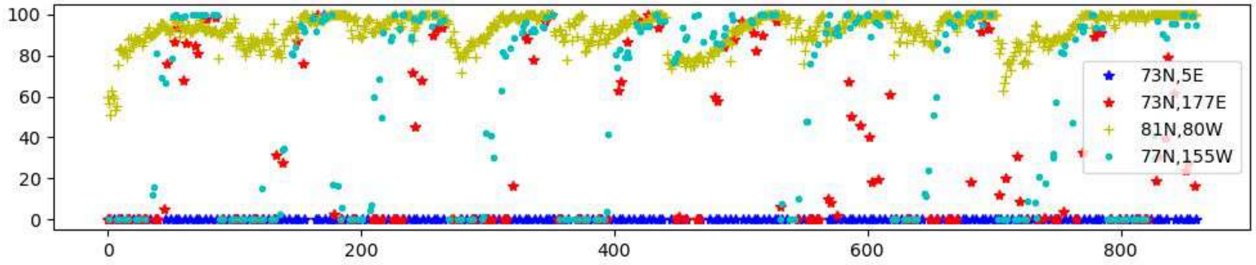
How these clouds can change surface warming?

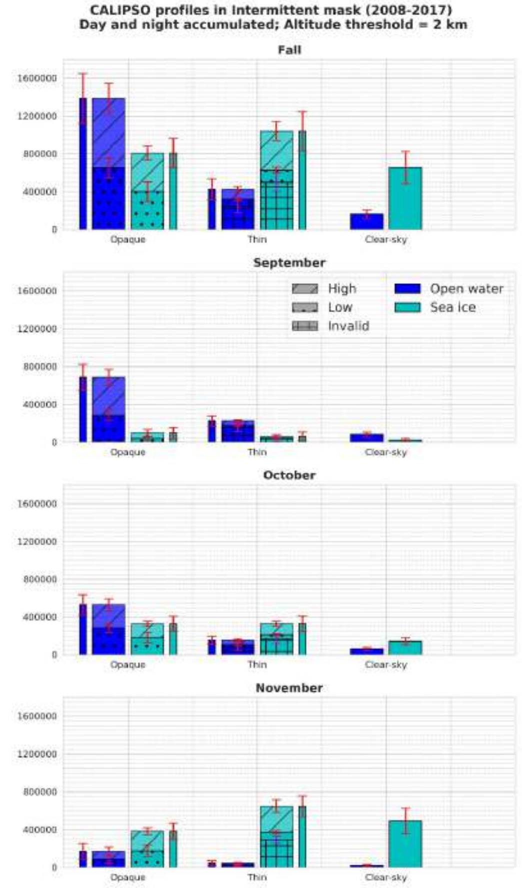


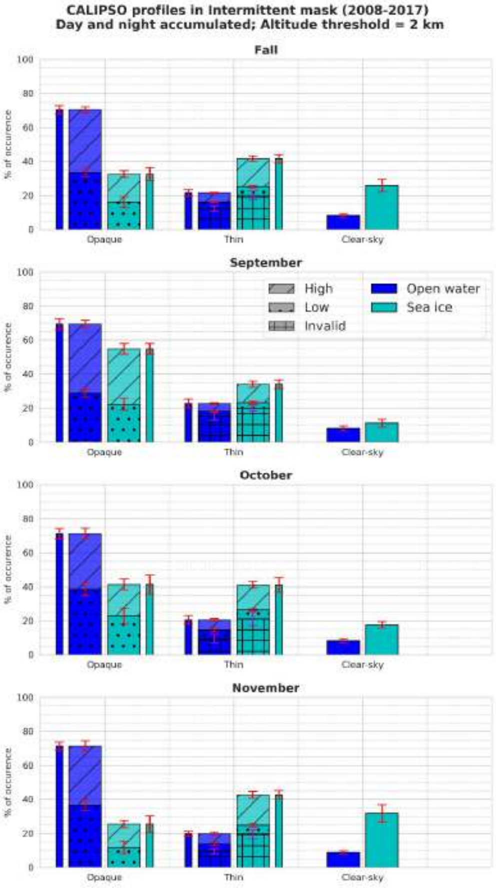

NCDIC sea ice cover daily 1°*1° from GOCCP files
JJA
SON
MAM
DJF
90°W
90°E
60°W
60°E
30°W
30°E
0°
0
12
25
38
50
62
75
88
100
cover (%)

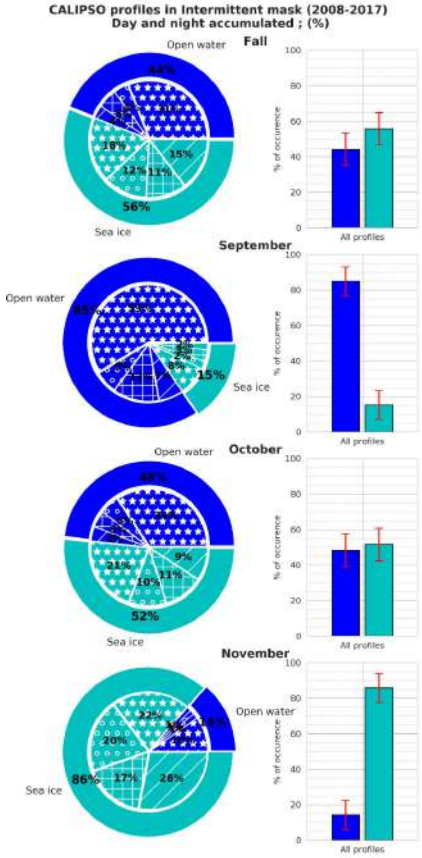
NCDIC sea ice cover daily 1°*1° from GOCCP files

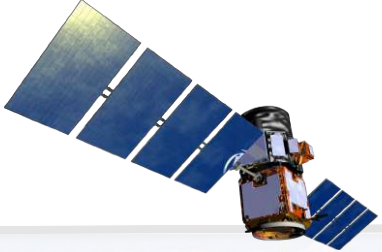


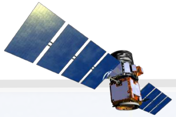



CALIPSO profiles in Intermittent mask (2008-2017)
Day and night accumulated; Altitude threshold = 2 km
Fall
September
October
November
High
Low
Invalid
Open water
Sea ice
Opaque
Thin
Clear-sky


CALIPSO profiles in Intermittent mask (2008-2017)
Day and night accumulated; Altitude threshold = 2 km
Fall
September
October
November
High
Low
Invalid
Open water
Sea ice
% of occurence
Opaque
Thin
Clear-sky


CALIPSO profiles in Intermittent mask (2008-2017)
Day and night accumulated ; (%)
Fall
Open water
Sea ice
44%
56%
September
85%
15%
October
48%
52%
November
14%
86%
% of occurence
All profiles





Surface longwave cloud radiative effect derived from space lidar observations: application in the Arctic

Annex A

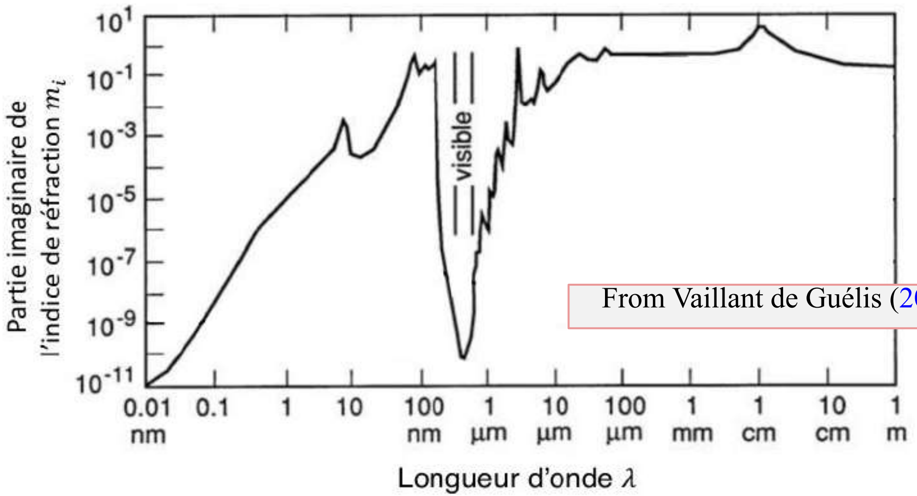
April 21st, 2023: PhD defense

Assia Arouf

Supervisor: Hélène Chepfer

Absorption by a cloud particle

➢ The absorption of radiation by a cloud particle depend only on the imaginary part of the index of refraction
  - in the VIS : m_i **is small** and cloud particle **absorption can be neglected**
  - in the IR : m_i **is large** and cloud particle **absorption is importante**



From Vaillant de Guélis (2017)

FIGURE A.6 : Partie imaginaire de l'indice de réfraction de l'eau en fonction de la longueur d'onde. Source : ZOLORATEV et DEMIN (1977)

Scattering by a cloud particle

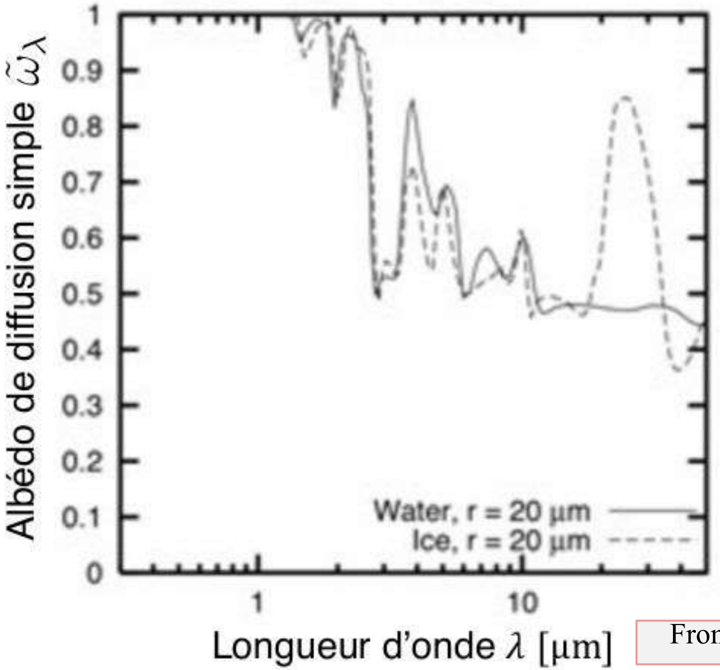


FIGURE A.9 : Albédo de diffusion simple pour une sphère d'eau liquide ou de glace de 20 μm de rayon en fonction de la longueur d'onde dérivé de la théorie de Mie. Source : Cours Patrick Arnott Chap. 12 – University of Nevada Reno.

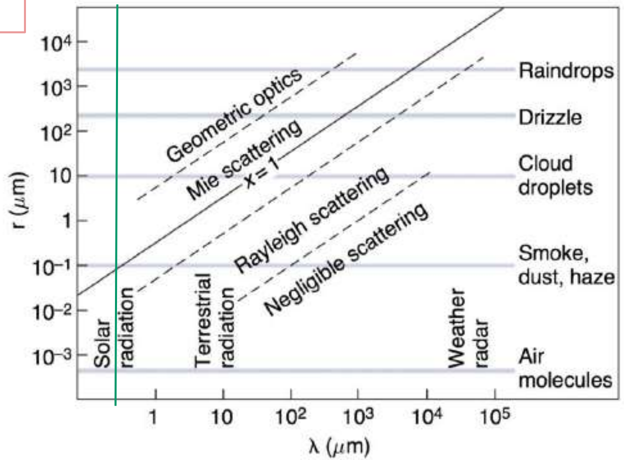
From Vaillant de Guélis (2017)

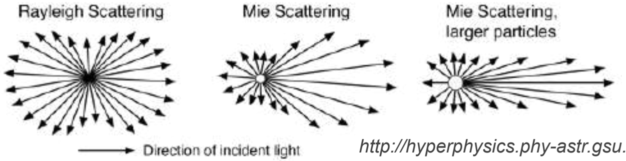
- In the **VIS** : $\tilde{\omega}_\lambda$ ***=1*** => cloud particle **scatter a lot**
- In the **IR** : $\tilde{\omega}_\lambda$ ~***0*** **=> scattering by clouds is small**

$$\tilde{\omega}_\lambda = \frac{\sigma_{\lambda,s}}{\sigma_{\lambda,e}}$$

size parameter

$$x = \frac{2\pi a}{\lambda}$$



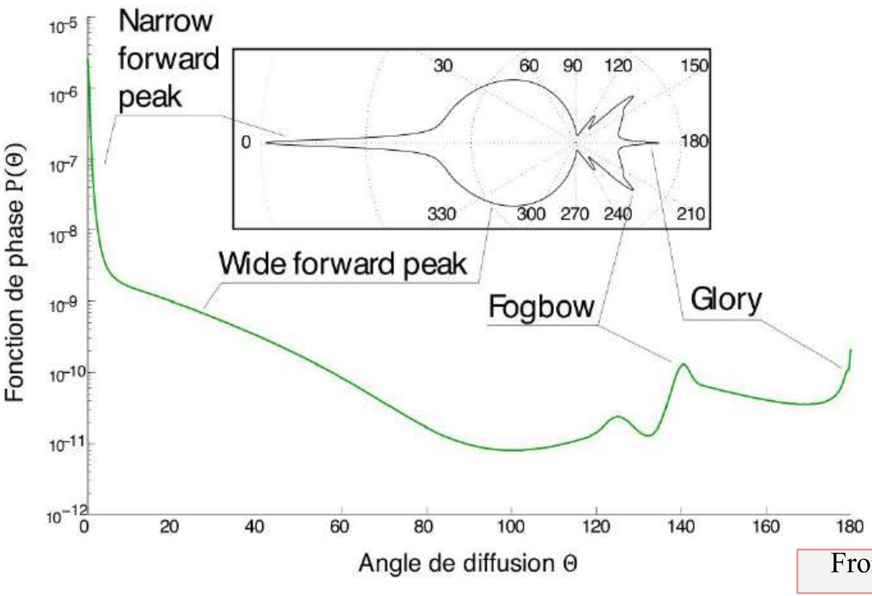


http://hyperphysics.phy-astr.gsu.edu

Fonction de phase

➢ Inform about the angular distribution of light scattered by a particul (depend on the wavelength, particle size, and particle optical property)

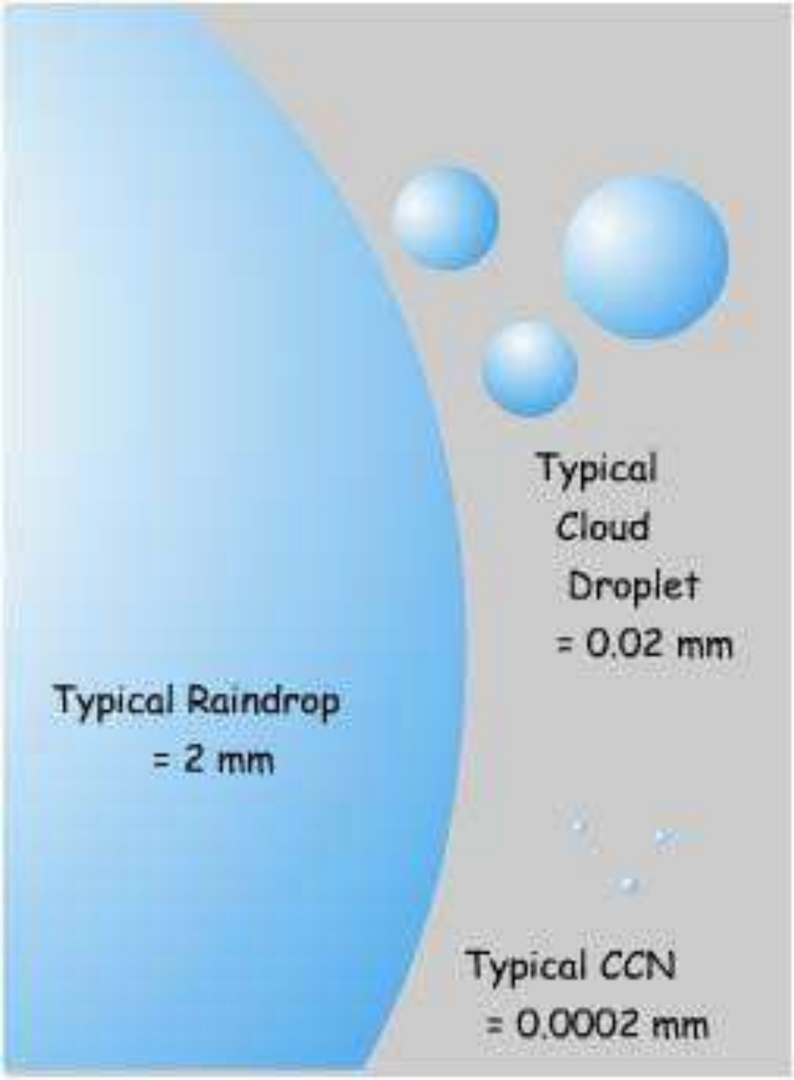
   ○ Plus la particule augmente par rapport à la longueur d'onde, elle aura tendance à diffuser vers l'avant. **Et créer de la diffusion multiple**



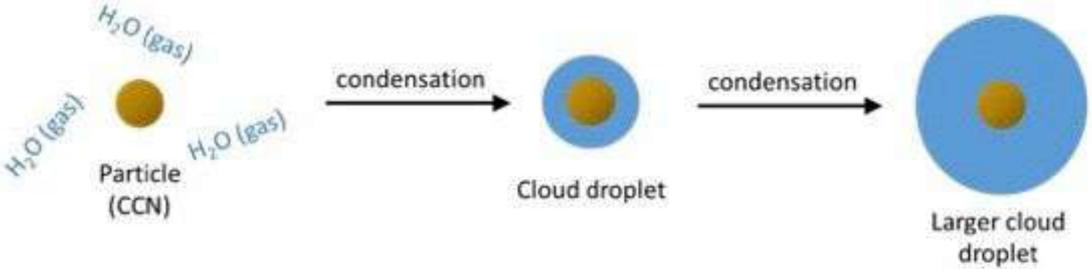
$\delta_{VIS} = 2^* \ \delta_{IR}$

From Vaillant de Guélis (2017)

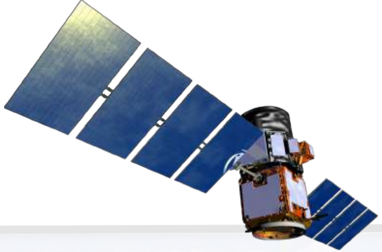
FIGURE B.3 : Fonction de phase $P(\Theta)$ en fonction de l'angle de diffusion Θ pour une gouttelette sphérique de $20\,\mu m$ pour un rayonnement incident correspondant à la longueur d'onde du vert. Source : BOUTHORS et al. (2006).

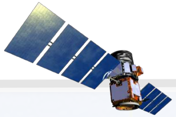


Typical Cloud Droplet = 0.02 mm
Typical Raindrop = 2 mm
Typical CCN = 0.0002 mm



H_2O (gas)
H_2O (gas)
H_2O (gas)
Particle (CCN)
condensation
Cloud droplet
condensation
Larger cloud droplet





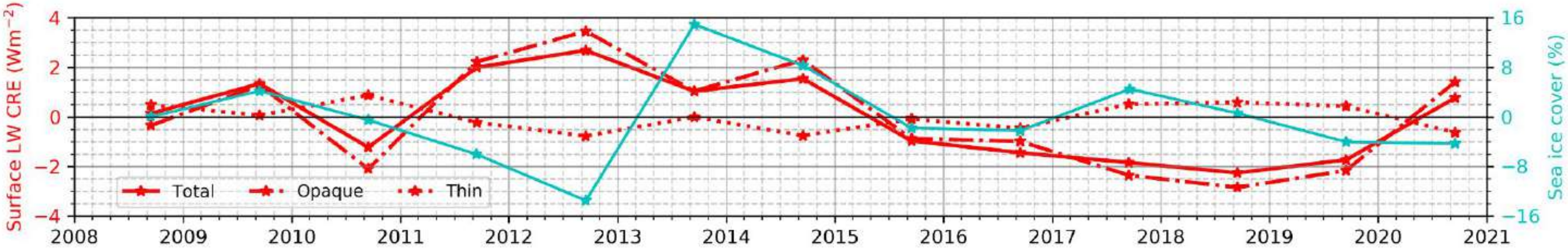
Surface longwave cloud radiative effect derived from space lidar observations: application in the Arctic

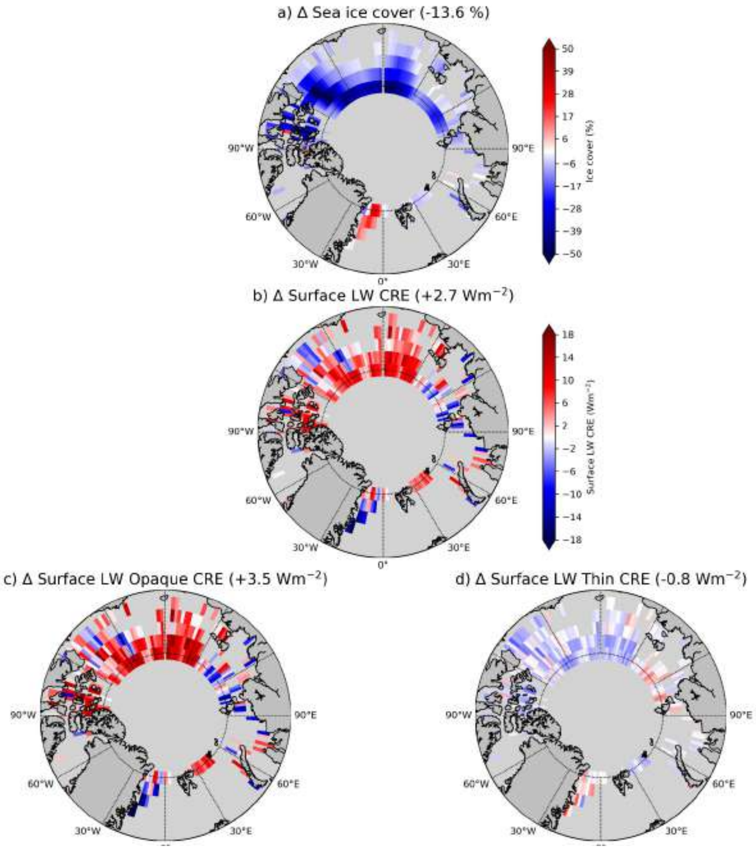
Annex C

April 21st, 2023: PhD defense

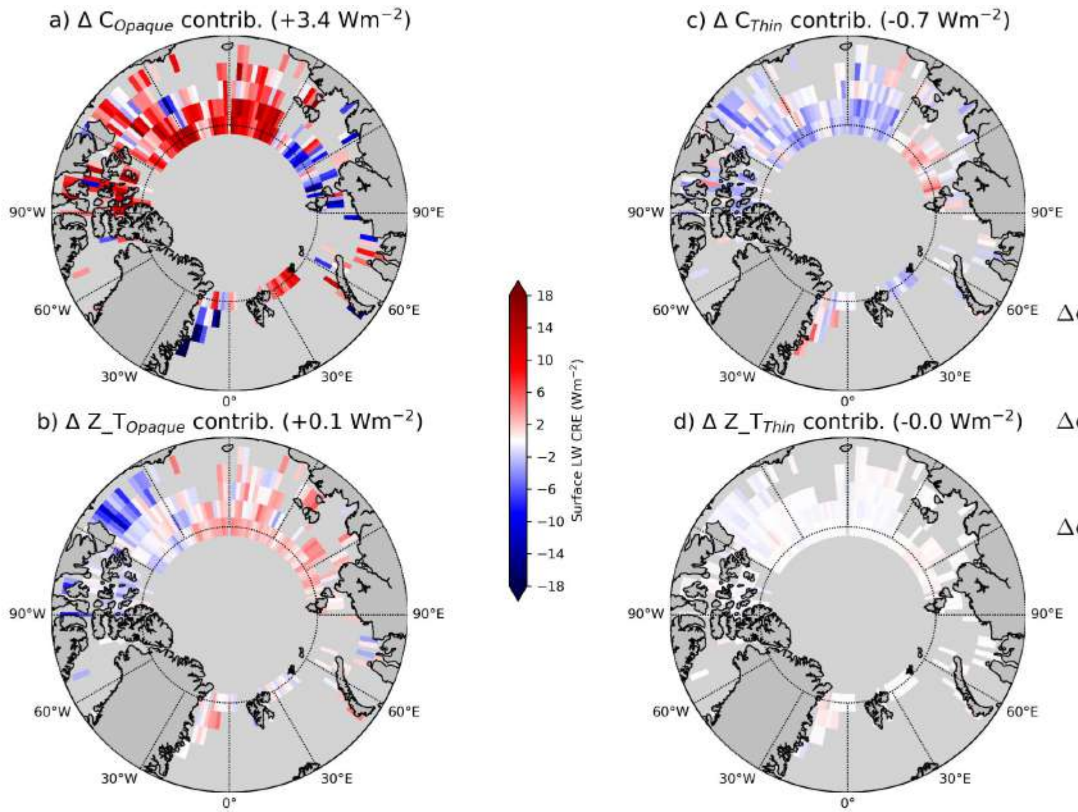
Assia Arouf

Supervisor: Hélène Chepfer


Surface LW CRE (Wm^{-2})
Sea ice cover (%)
Total
Opaque
Thin
4
2
0
−2
−4
16
8
0
−8
−16
2008
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021



(Vaillant de Guélis et al., 2017a : Obs TOA)
(Zhou et al., 2014 : Cirrus)
(Zelinka et al., 2012 : Models)

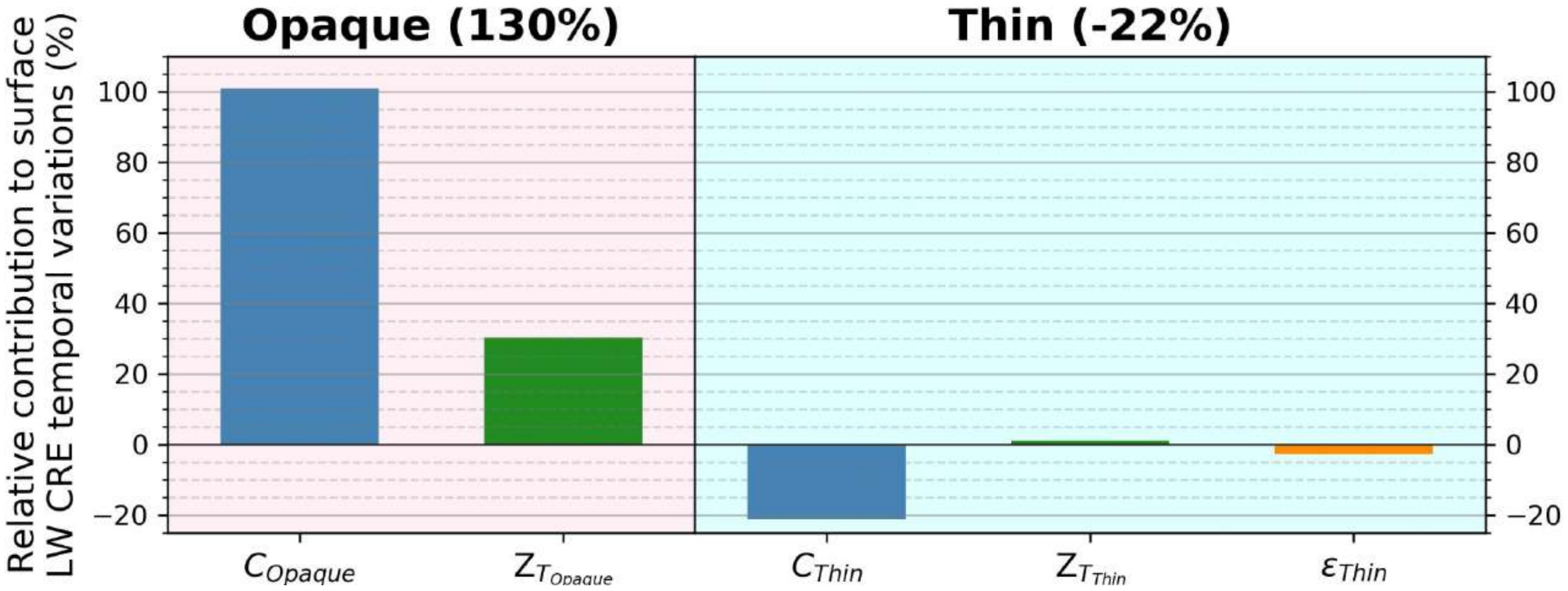


$$\Delta CRE^{SFC}_{Opaque} = \frac{\partial CRE_{Opaque}}{\partial C_{Opaque}}\Delta C_{Opaque} + \frac{\partial CRE_{Opaque}}{\partial Z_{Opaque}}\Delta Z_{Opaque}$$

$$\Delta CRE^{SFC}_{Thin} = \frac{\partial CRE_{Thin}}{\partial C_{Thin}}\Delta C_{Thin} + \frac{\partial CRE_{Thin}}{\partial Z_{Thin}}\Delta Z_{Thin} + \frac{\partial CRE_{Thin}}{\partial \varepsilon_{Thin}}\Delta \varepsilon_{Thin}$$

$$\Delta CRE^{SFC}_{Total} = \Delta CRE^{SFC}_{Opaque} + \Delta CRE^{SFC}_{Thin}$$

(Vaillant de Guélis et al., 2017b : Obs TOA)
(Zhou et al., 2014 : Cirrus)
(Zelinka et al., 2012 : Models)



$$X_i = \frac{cov(\Delta CRE^{SFC}_{Total}(t), \Delta CRE^{SFC}_{V_i}(t))}{\sigma^2_{\Delta CRE^{SFC}_{Total}}(t)}$$

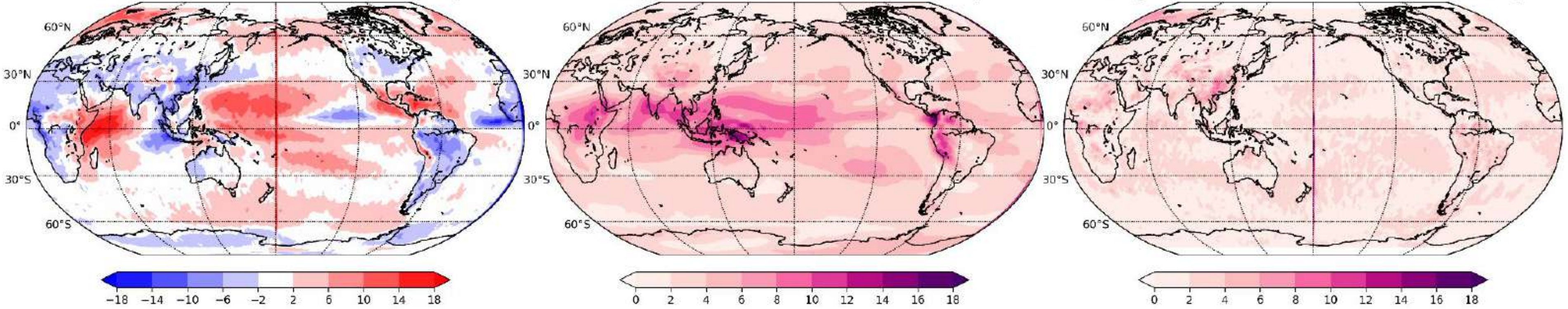
(Vaillant de Guélis et al., 2017b)
(Boer and Yu., 2003 : Spatial)

Incertitude de l'effet radiatif LW des nuages des modèles CMIP6

Preliminary

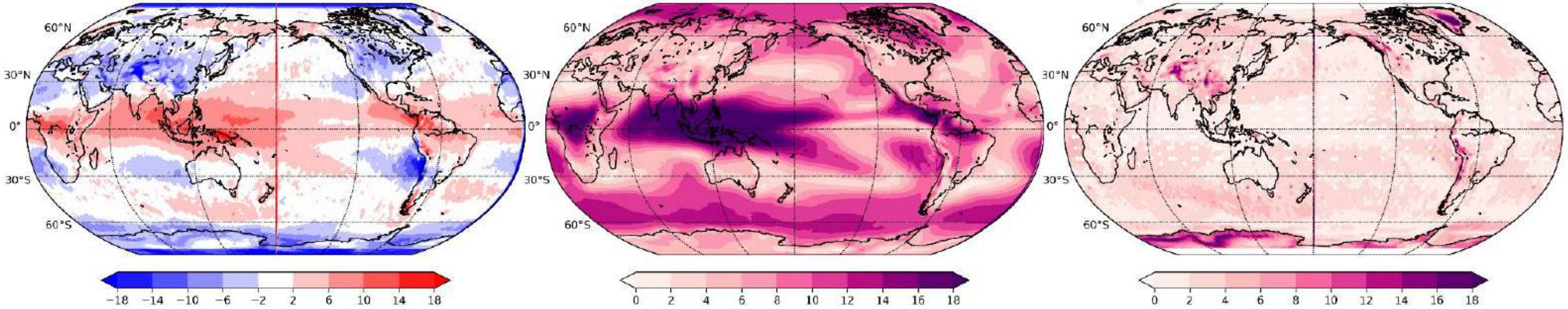
TOA

Biais moyen des modèles (1.0 W m^{-2}) | **Dispersion inter-modèles (4.0 W m^{-2})** | **Dispersion inter-observations (1.8 W m^{-2})**



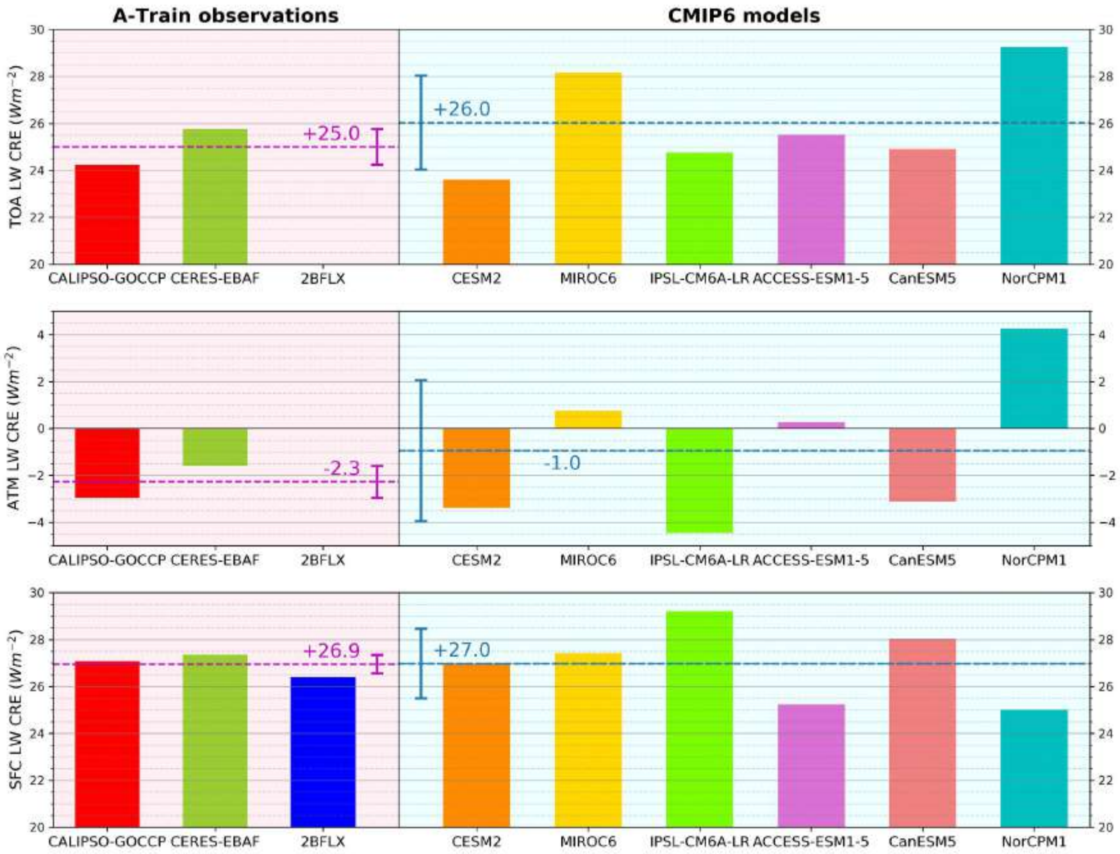
SFC

Biais moyen des modèles (0.6 W m^{-2}) | **Dispersion inter-modèles (8.5 W m^{-2})** | **Dispersion inter-observations (2.5 W m^{-2})**



Incertitude sur la moyenne globale de l'effet radiatif LW des nuages

Preliminary



(2008–2014)

TOA	Biais moyen des modèles **+1.0 W m^{-2}** Variance sur la moyenne globale **±1.8 W m^{-2}**
ATM	Biais moyen des modèles **+1.3 W m^{-2}** Variance sur la moyenne globale **±2.7 W m^{-2}**
SFC	Biais moyen des modèles **+0.1 W m^{-2}** Variance sur la moyenne globale **±1.2 W m^{-2}**