Polar Clouds

Microphysics, observed properties and representation in global climate models

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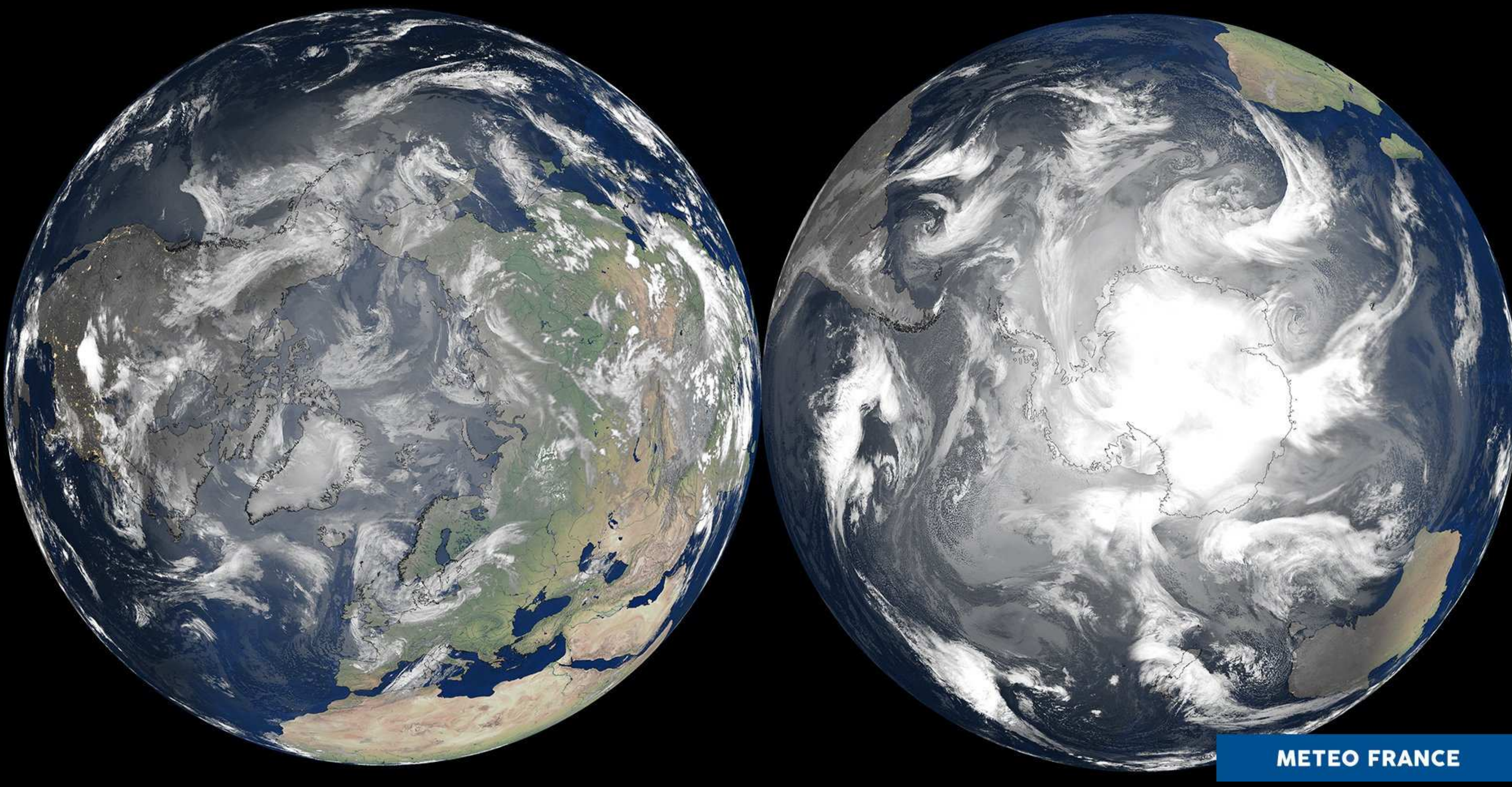
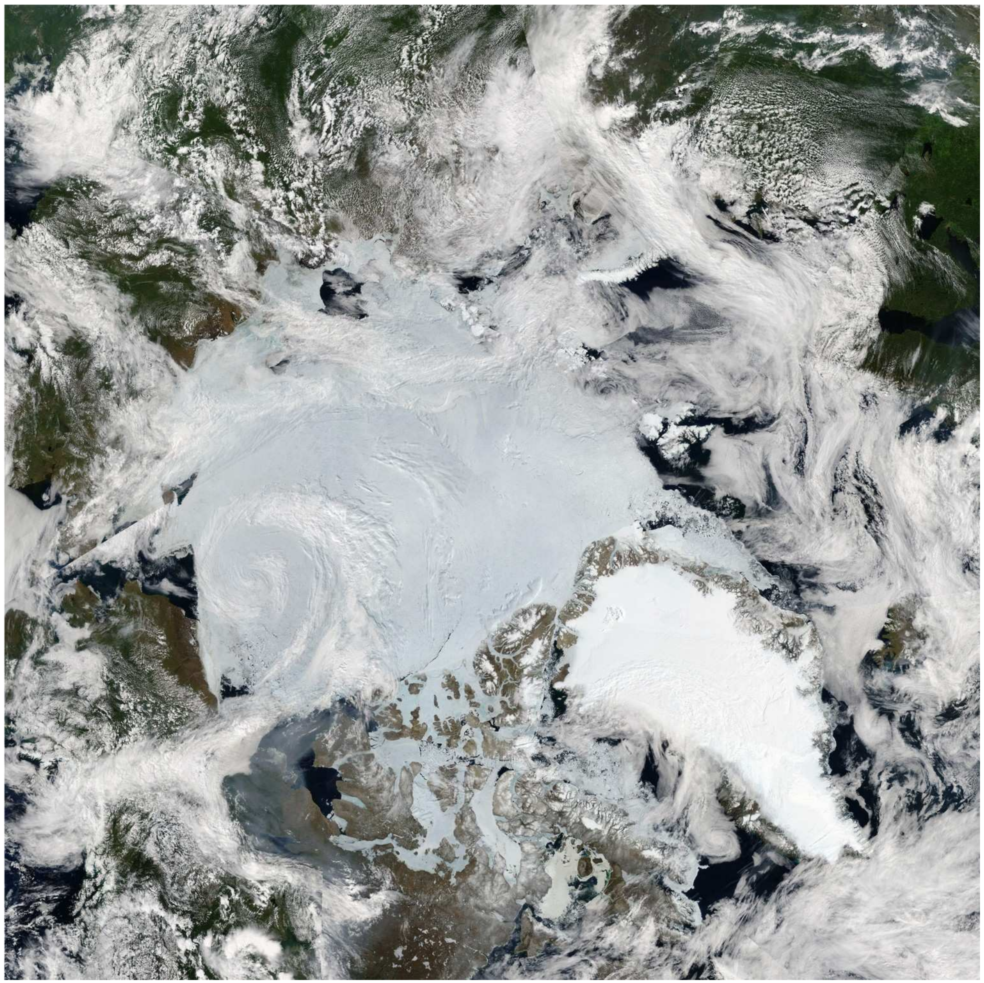
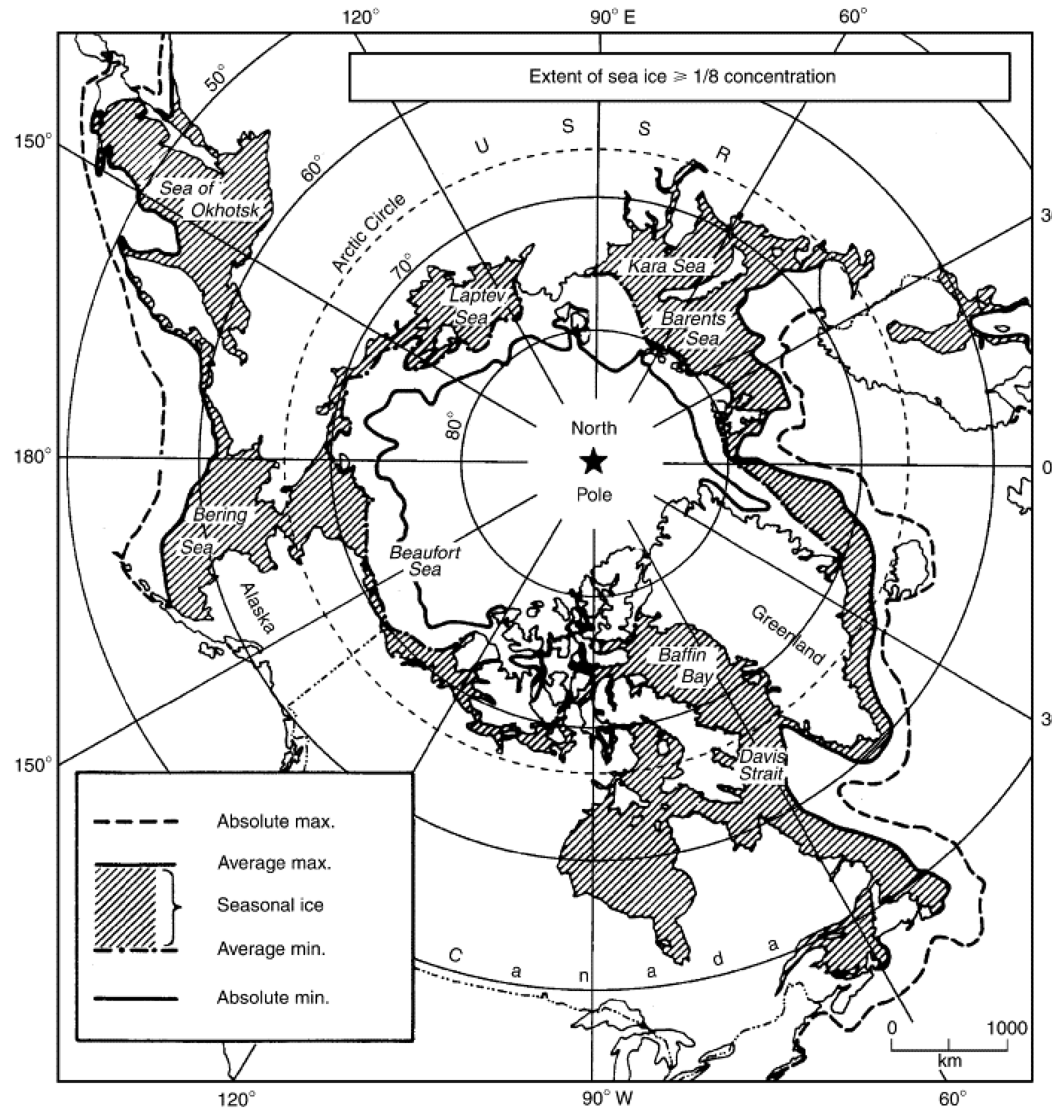
Arctic and Antarctic clouds



Link to animation

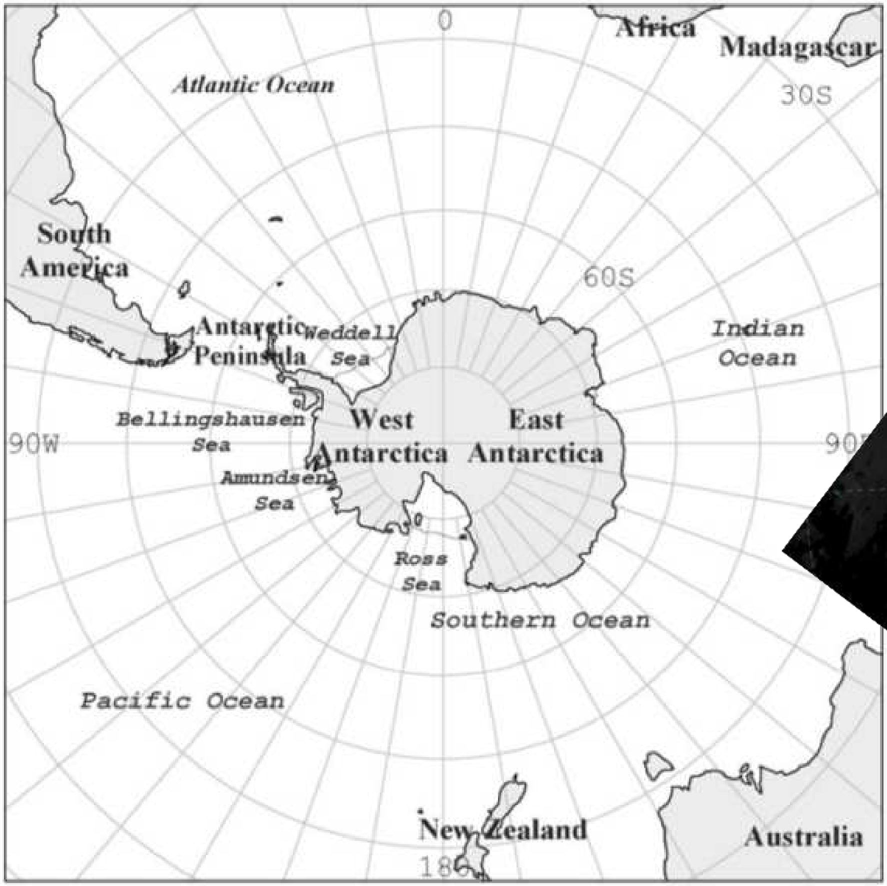
Arctic environment

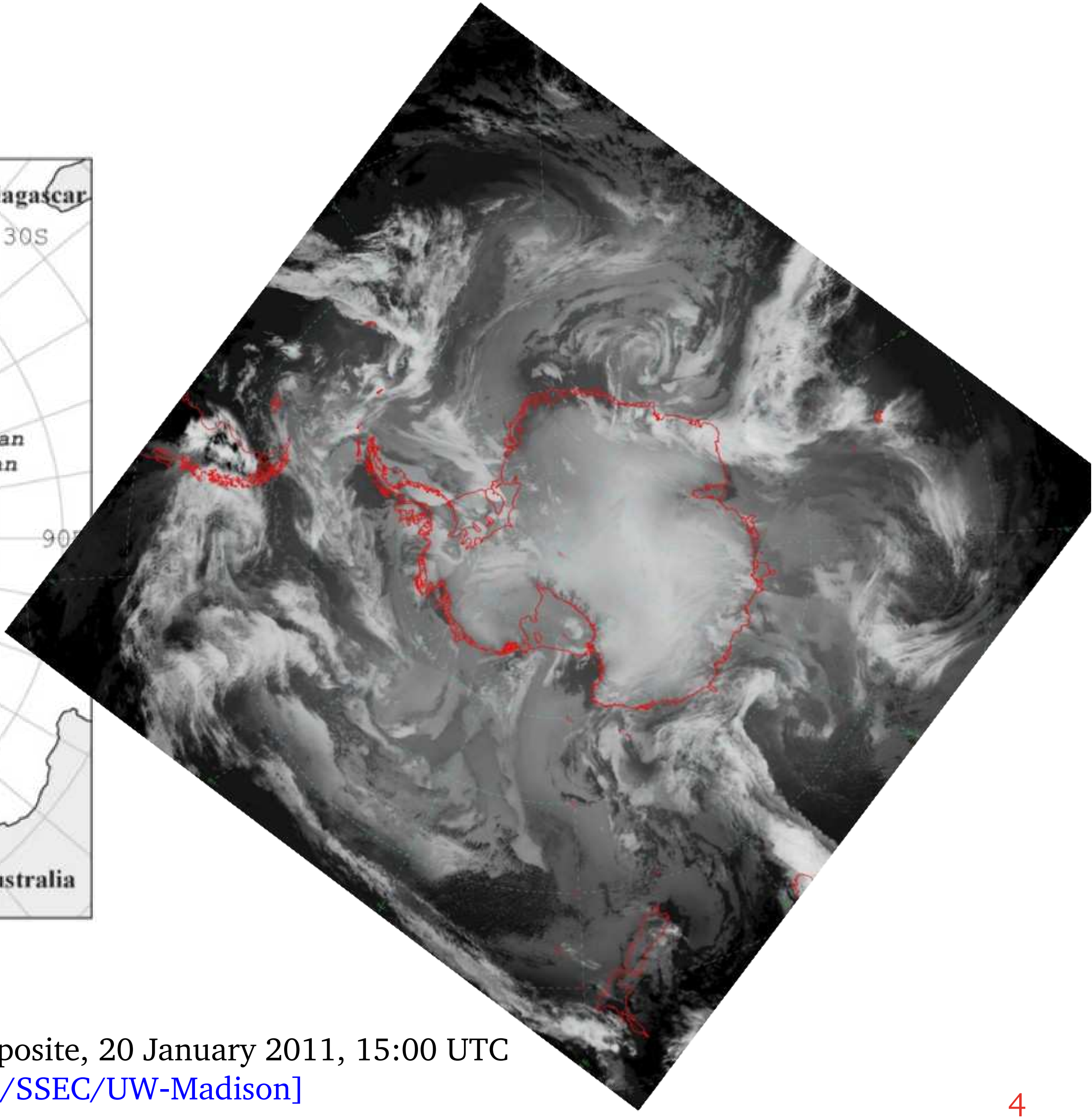




Arctic in late June, 2010 [MODIS image]

Antarctic environment

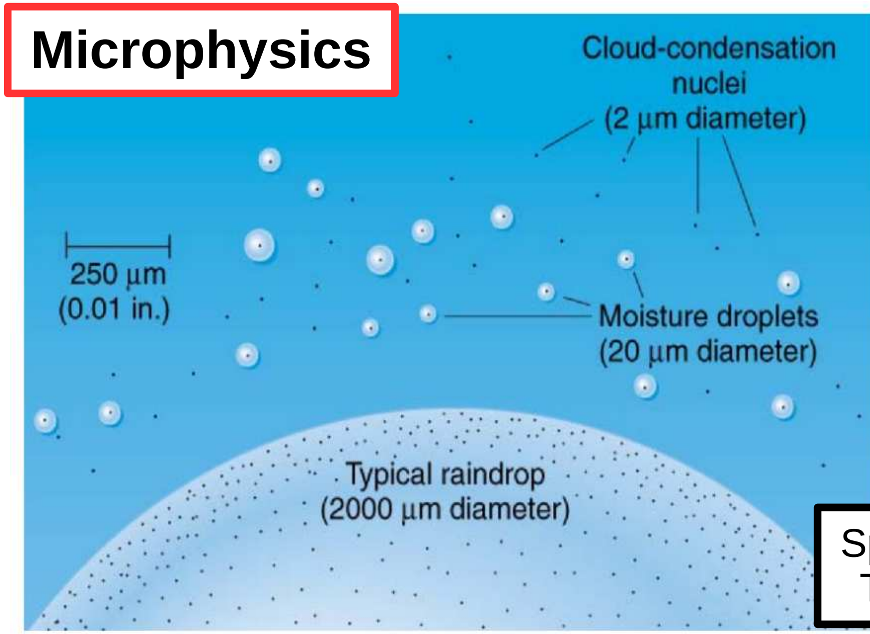




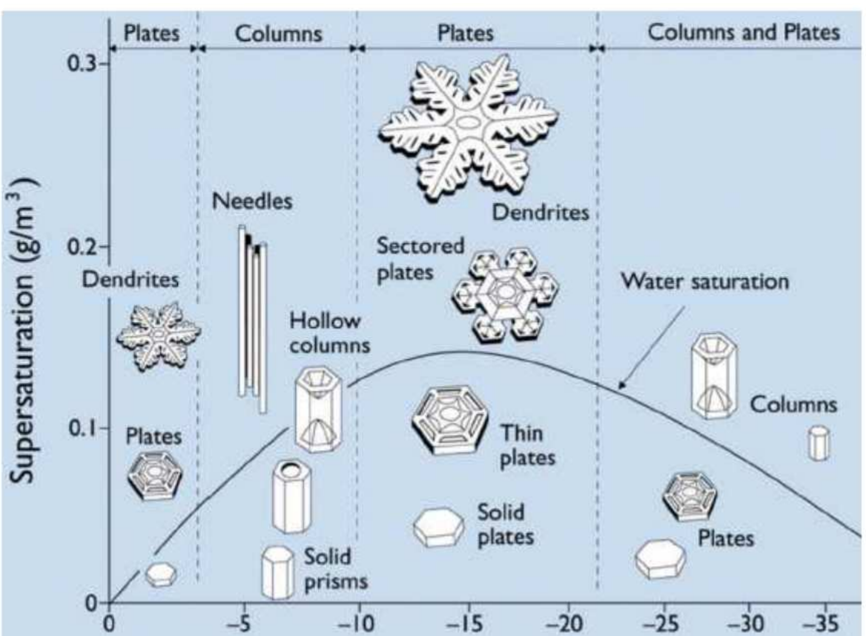
IR composite, 20 January 2011, 15:00 UTC
[AMRC/SSEC/UW-Madison]

Cold cloud microphysics and macrophysics

Microphysics

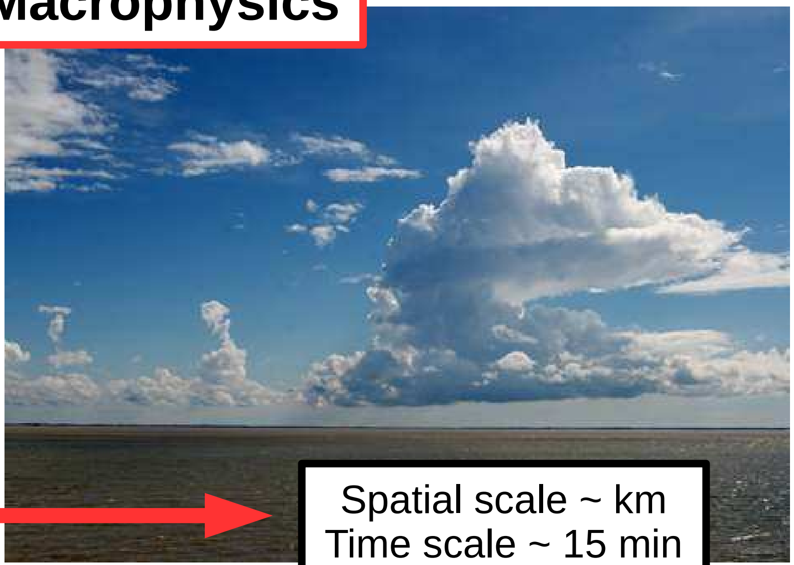


Spatial scale ~ µm
Time scale ~ 1 s



[Libbrecht, 2005]

Macrophysics



Spatial scale ~ km
Time scale ~ 15 min

Water saturation

- Clausius-Clapeyron equation :

$$\frac{1}{e_{\rm sat}}\frac{\mathrm{d}e_{\rm sat}}{\mathrm{d}T} = \frac{L}{R_{\rm vap}T^2}$$

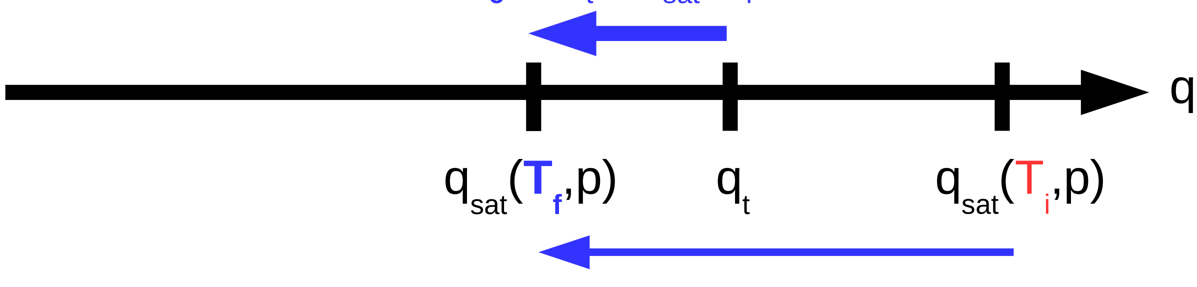
T	$0°\mathrm{C}$	$20°\mathrm{C}$
$e_{\rm sat}$	6.1 hPa	23.4 hPa
$q_{\rm sat}$	$3.7\ \mathrm{g\ kg^{-1}}$	$14.4\ \mathrm{g\ kg^{-1}}$

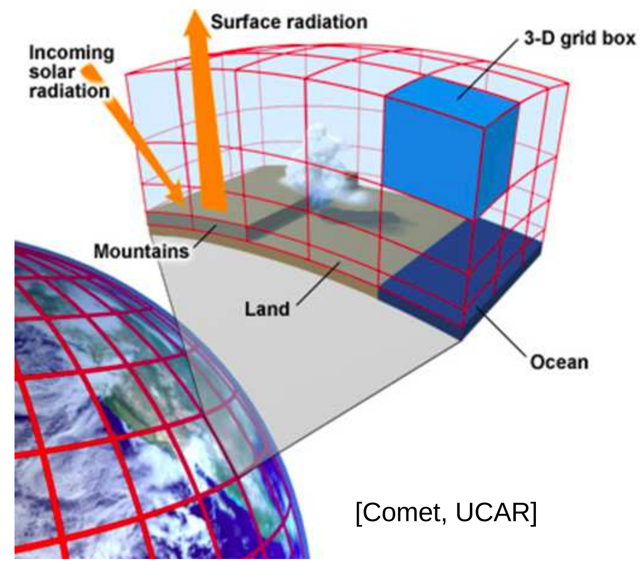
- Saturation mass mixing ratio :

$q_{sat}(T,p) \simeq 0.622\ \frac{e_{sat}(T)}{p}$, where $e_{sat}(T)$ grows exponentially with temperature

- Clouds form when an air parcel is cooled :

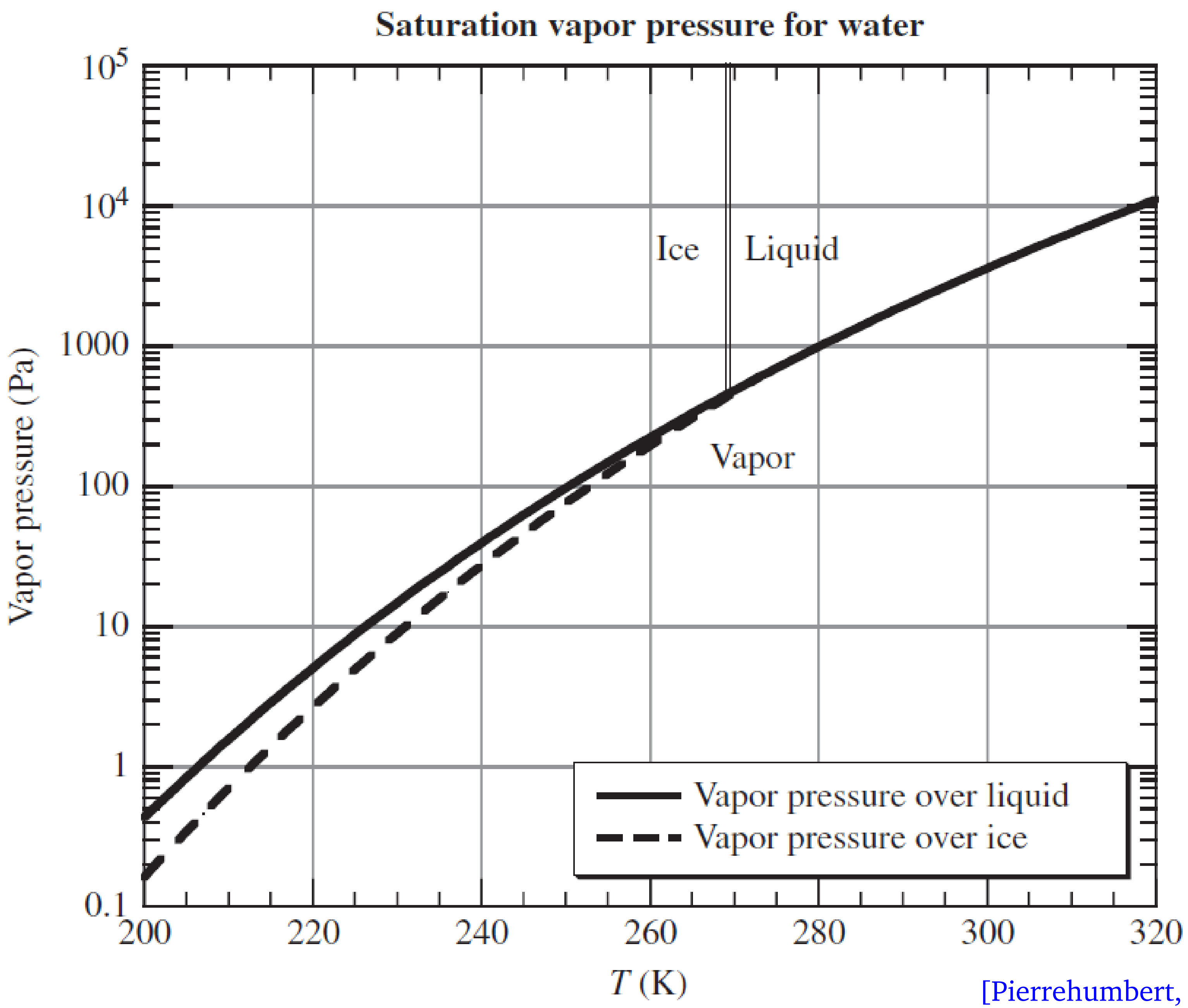
$\mathbf{q_c} = q_t - q_{sat}(T_f,p)$





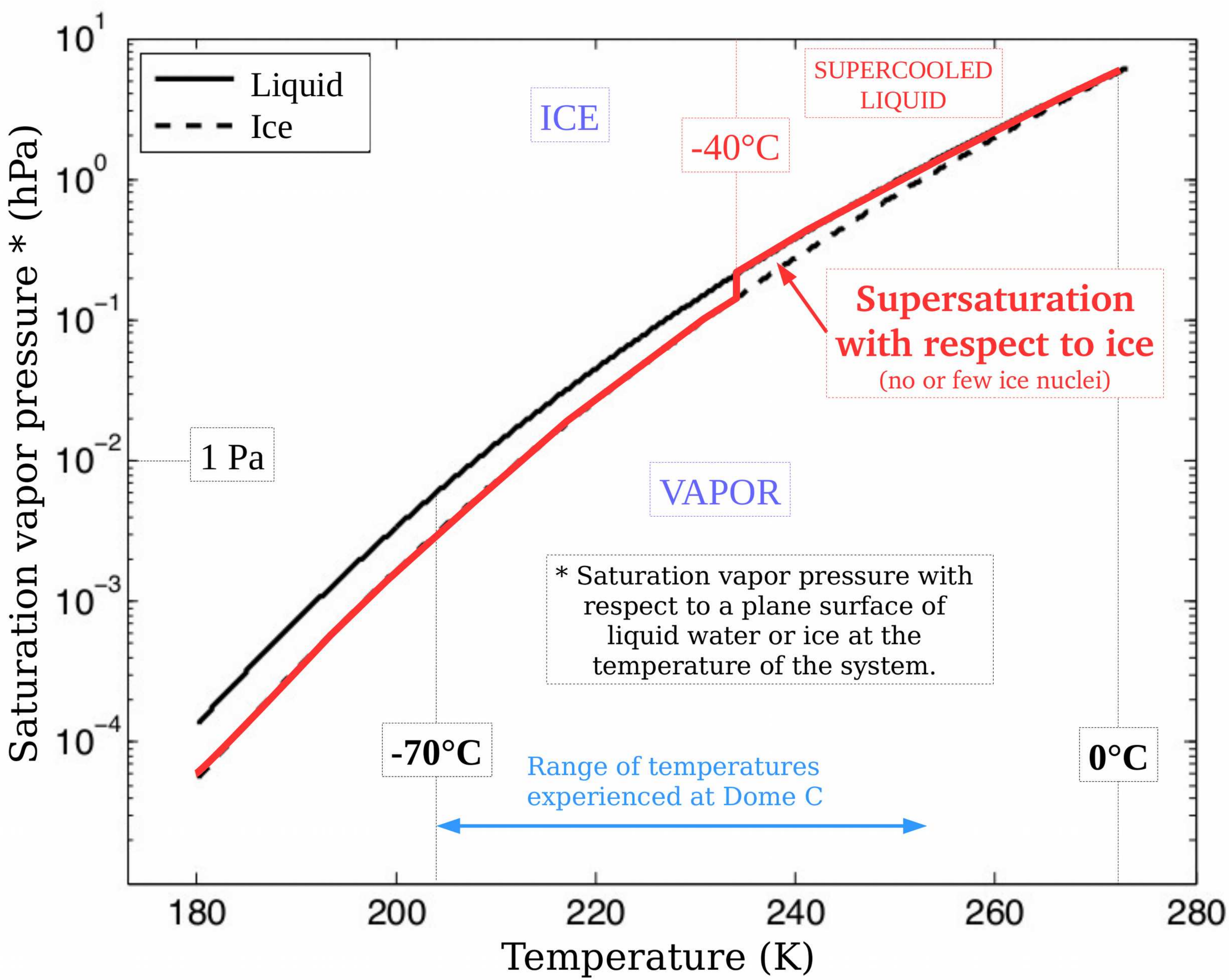
[Comet, UCAR]

Saturation vapor pressure

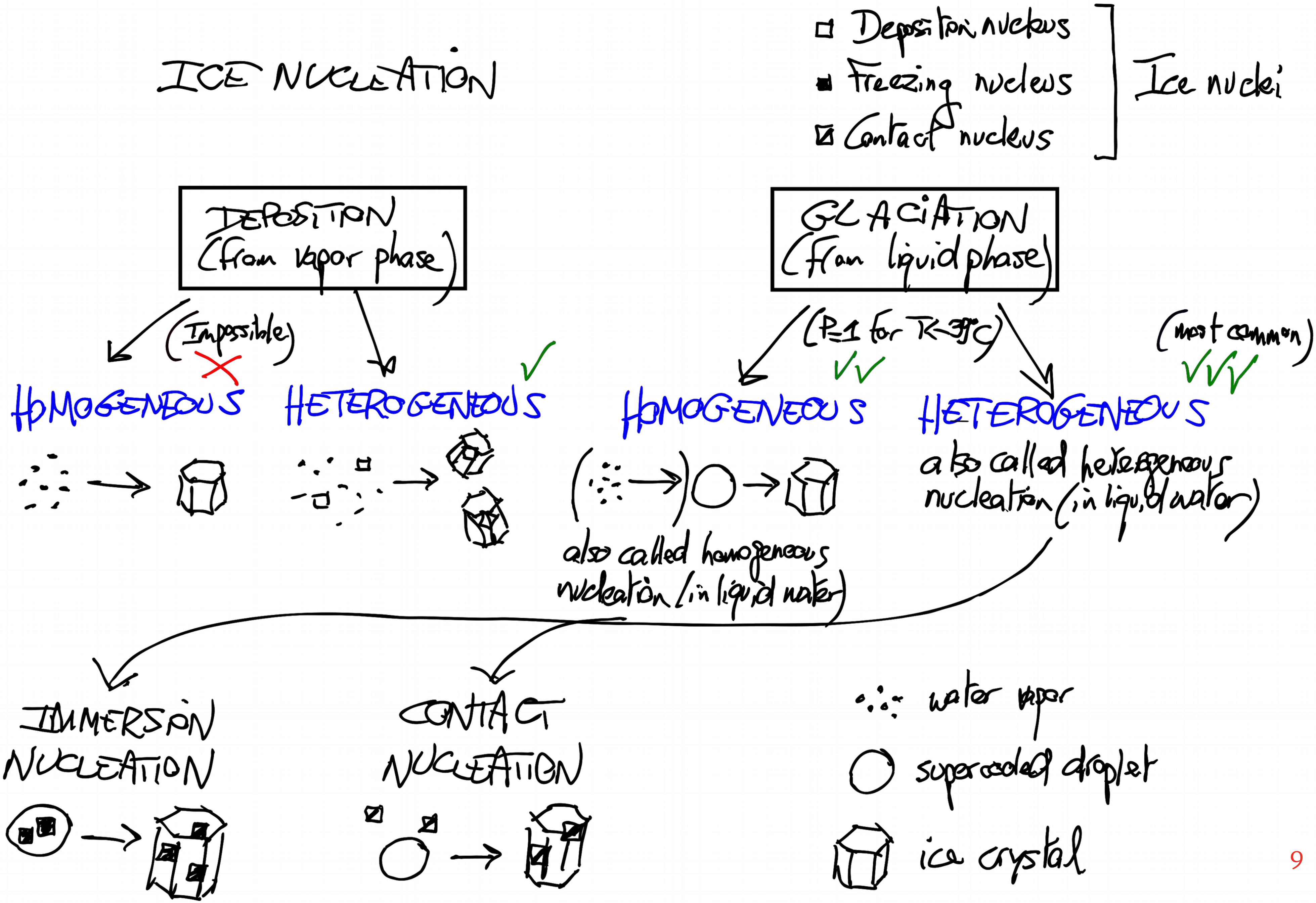


[Pierrehumbert, 2012]

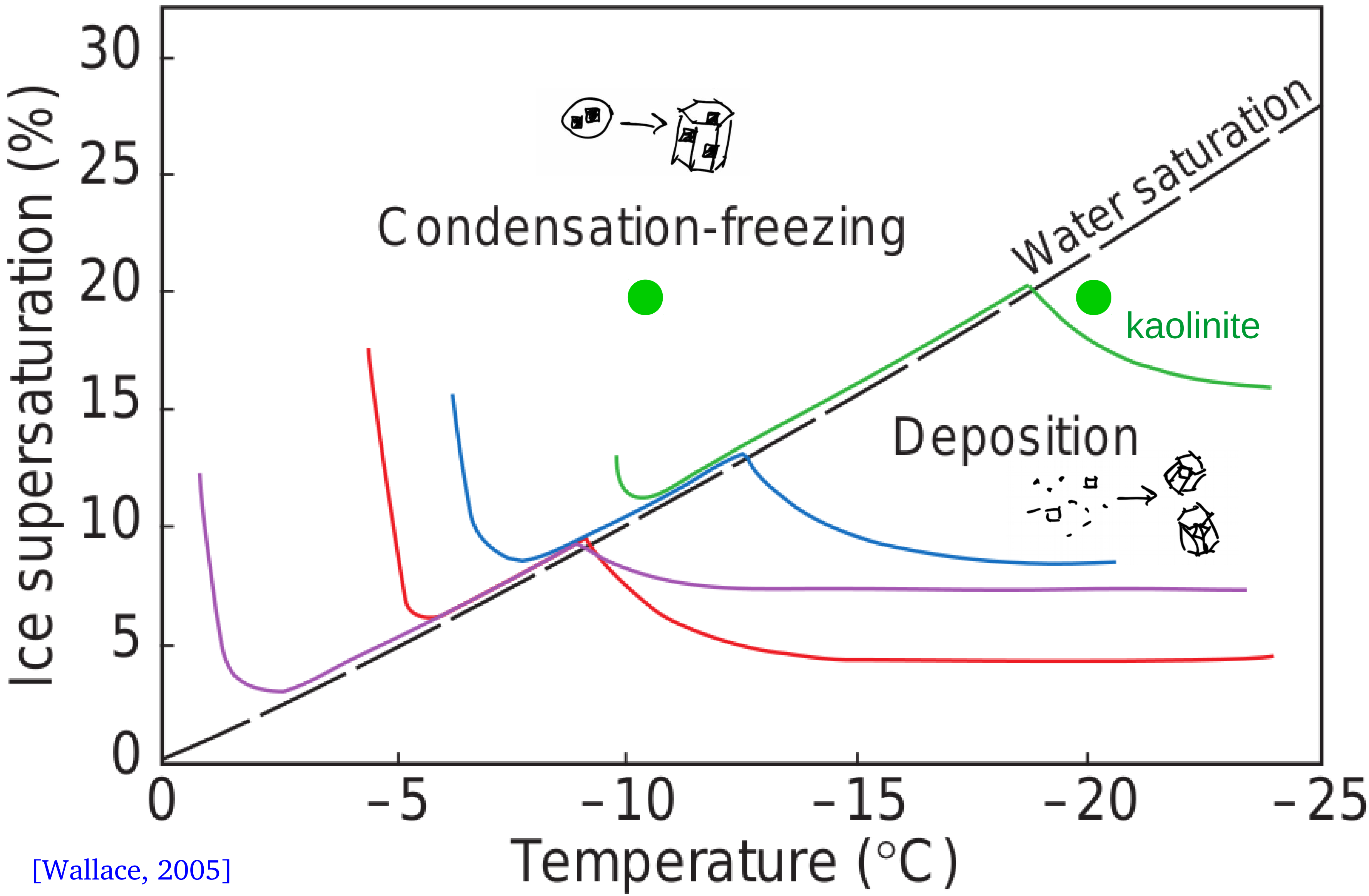
Supersaturation with respect to ice (wri)



Cold clouds : Microphysical processes



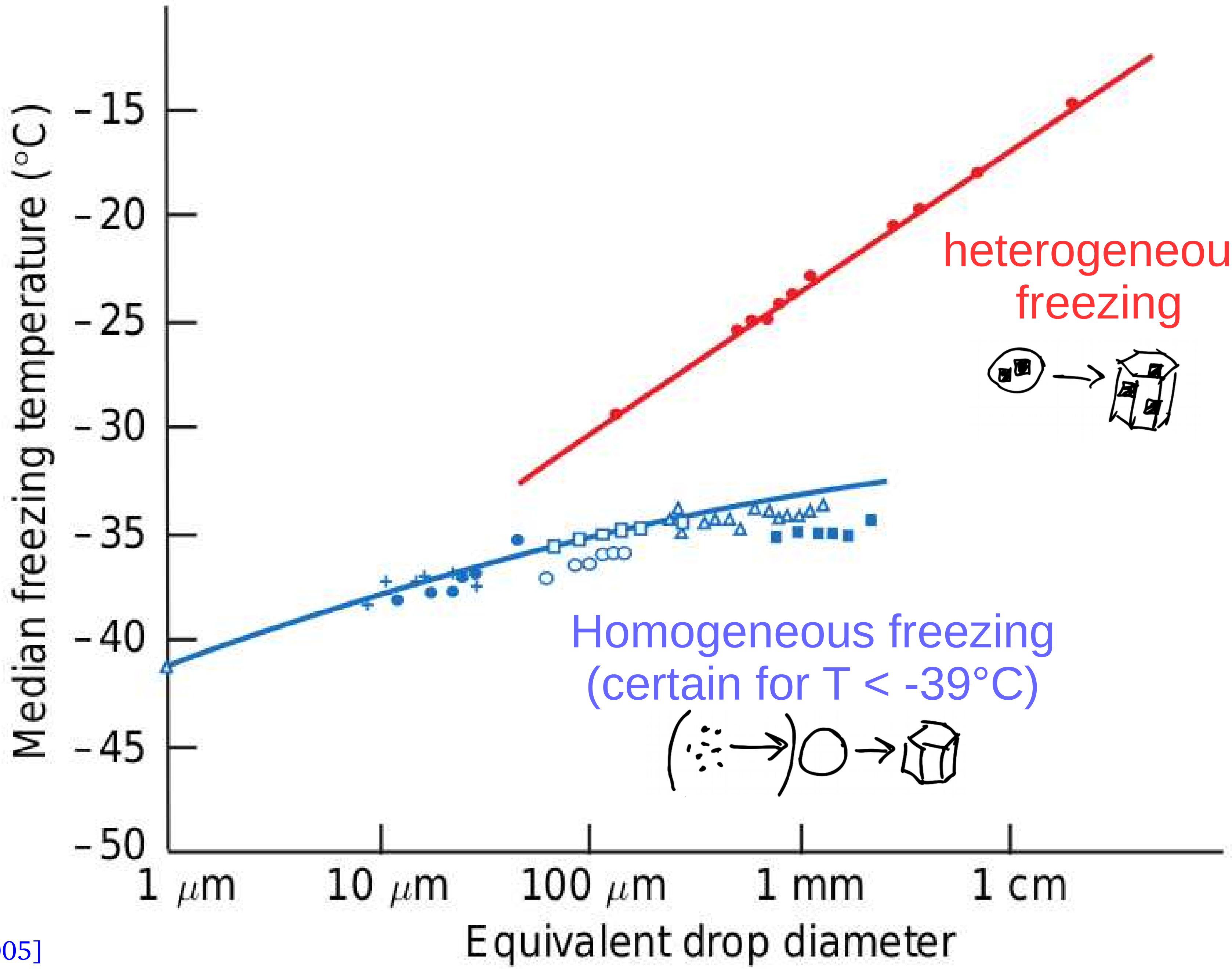
Deposition nuclei



[Wallace, 2005]

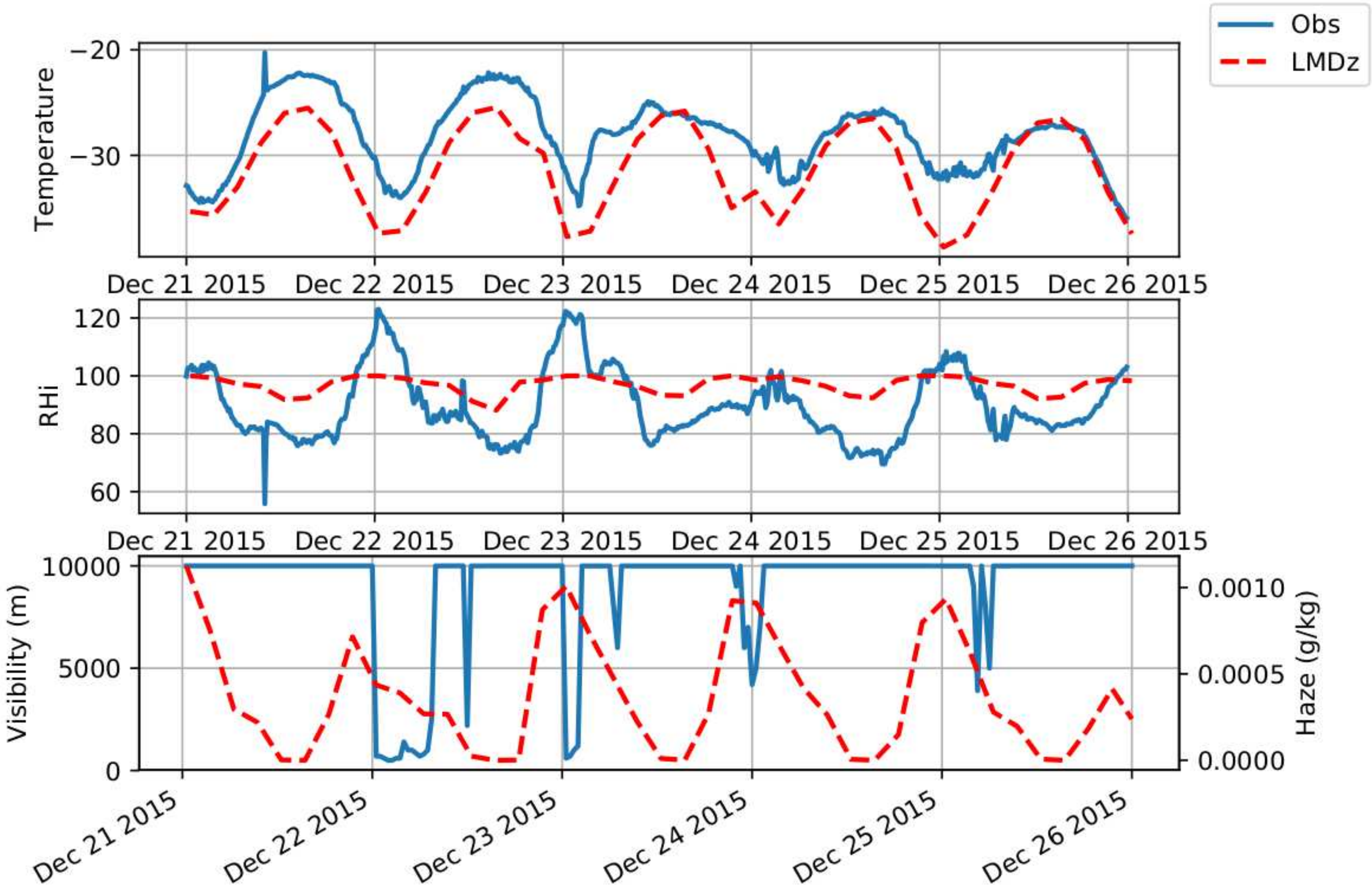
Silver iodide (red), lead iodide (blue), methaldehyde (purple), and kaolinite (green)

Homogeneous / Heterogeneous nucleation



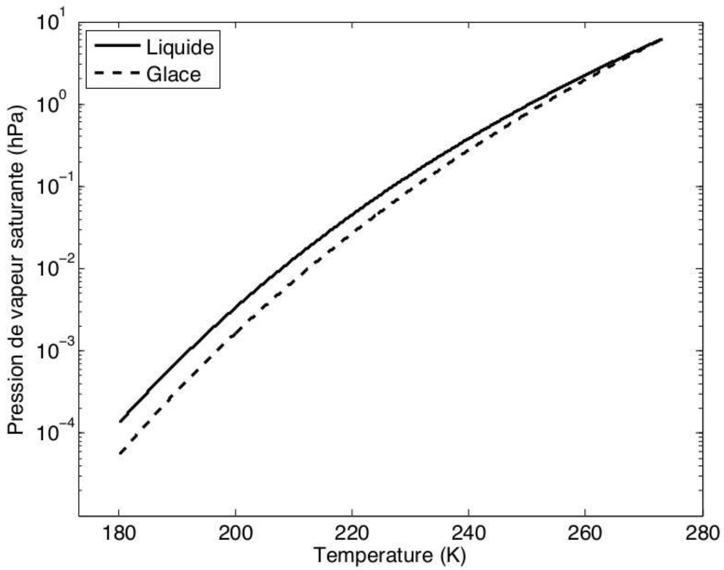
[Wallace, 2005]

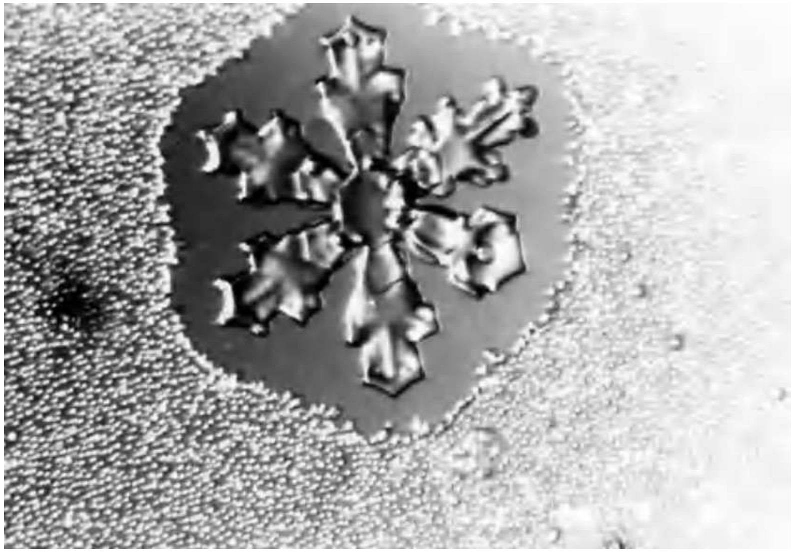
Supersaturation w.r.i. at Dome C, Antarctica



[Madeleine et al., in preparation]

Wegener–Bergeron–Findeisen process

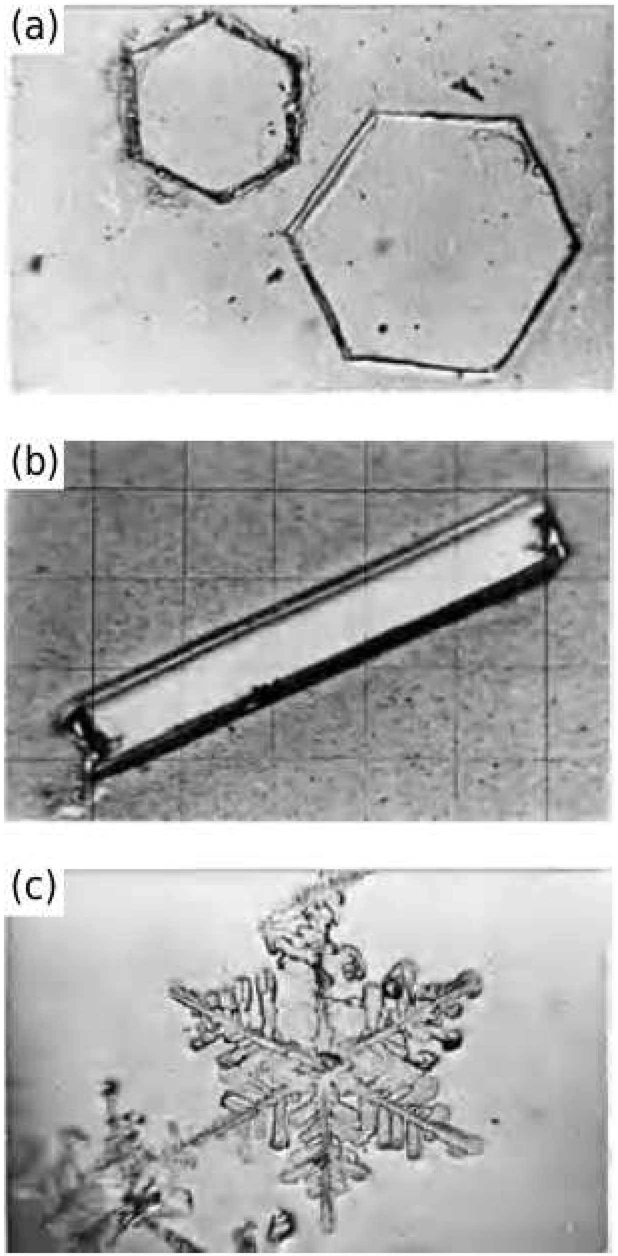


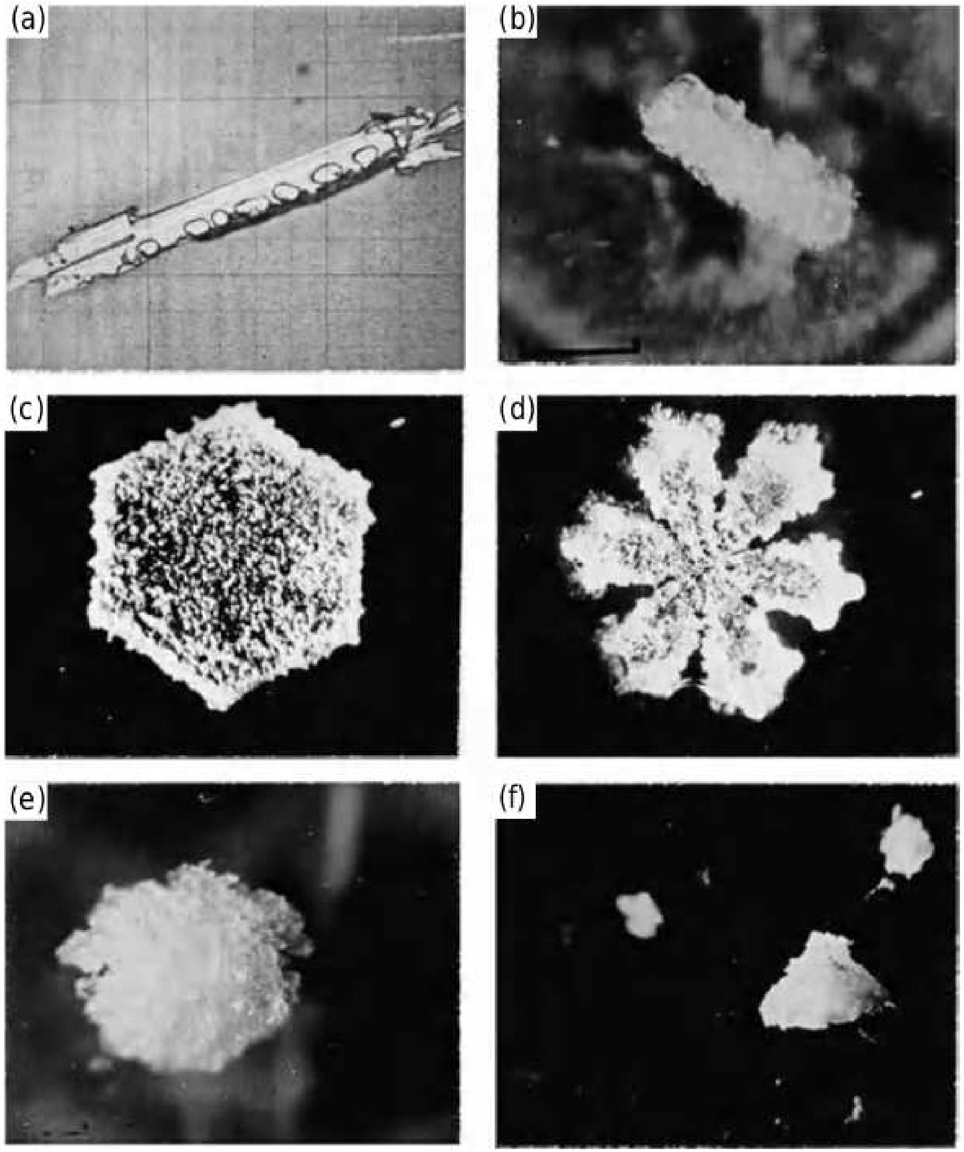


Growth of an ice crystal at the expense of surrounding supercooled water drops [Wallace, 2005]

Fallstreak hole (also known as hole punch clouds), Rhode Island, USA

Microphysical variety





[Wallace, 2005]

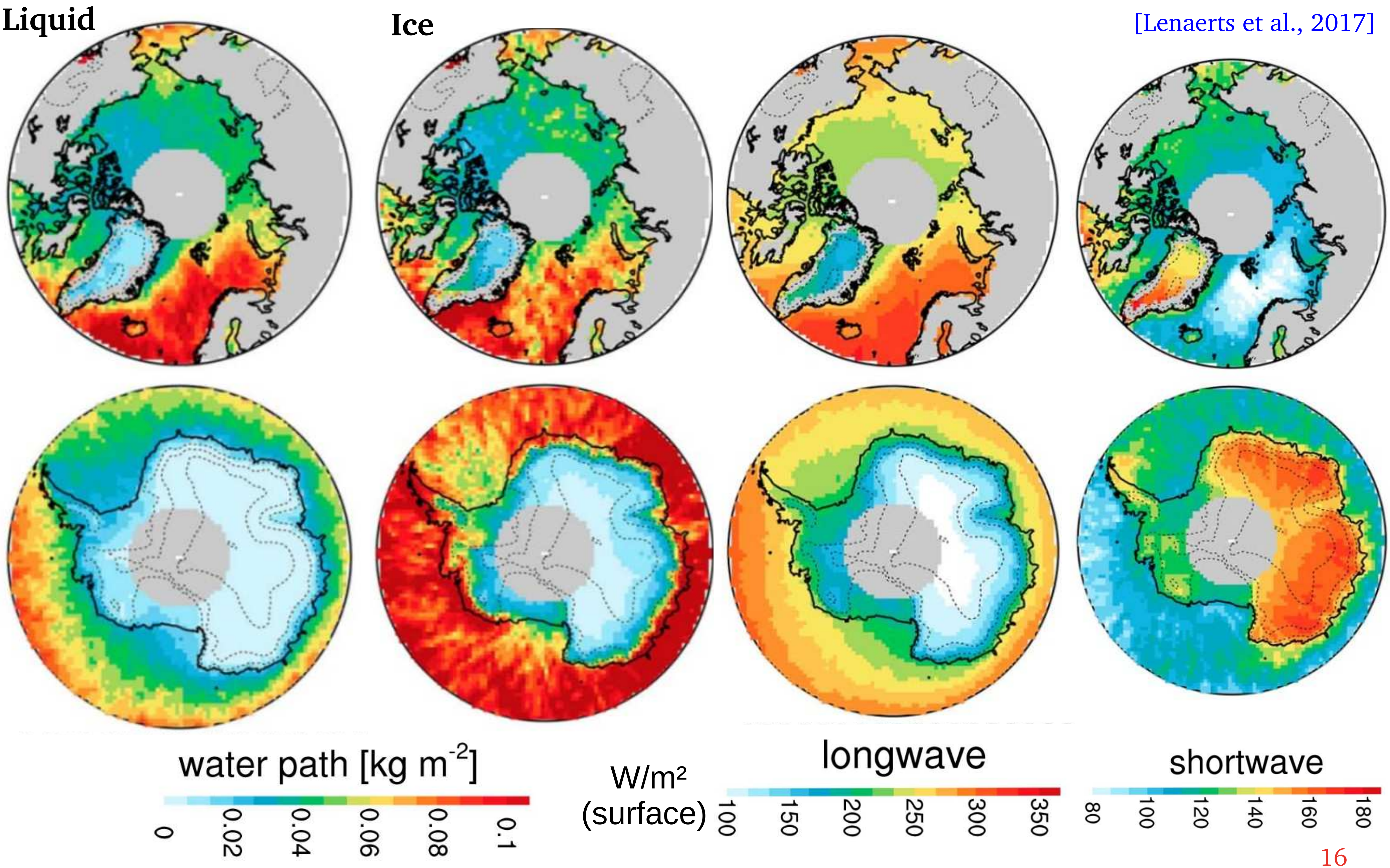
Typical timescales

Process	Timescale	Conditions
Homogeneous/hetero-genous nucleation	Seconds - minutes	
Deposition	30 minutes (example given to show that riming is way more efficient ; 30min deposition would not occur in real world !)	Hexagonal plate, -5°C, r=0.5mm
Riming	Few minutes	Plane plate of r=0.5mm in 0,5g/m³ liquid droplets → r=0.5mm graupel
Aggregation	~30 minutes	r=0.5mm→ r=0.5cm for 1g/m³ of ice
Sedimentation	~1 m/s	Snow of r=0.5cm

Whole precipitation process ~ 40 min

Polar clouds observed by CloudSat-CALIPSO

[Lenaerts et al., 2017]



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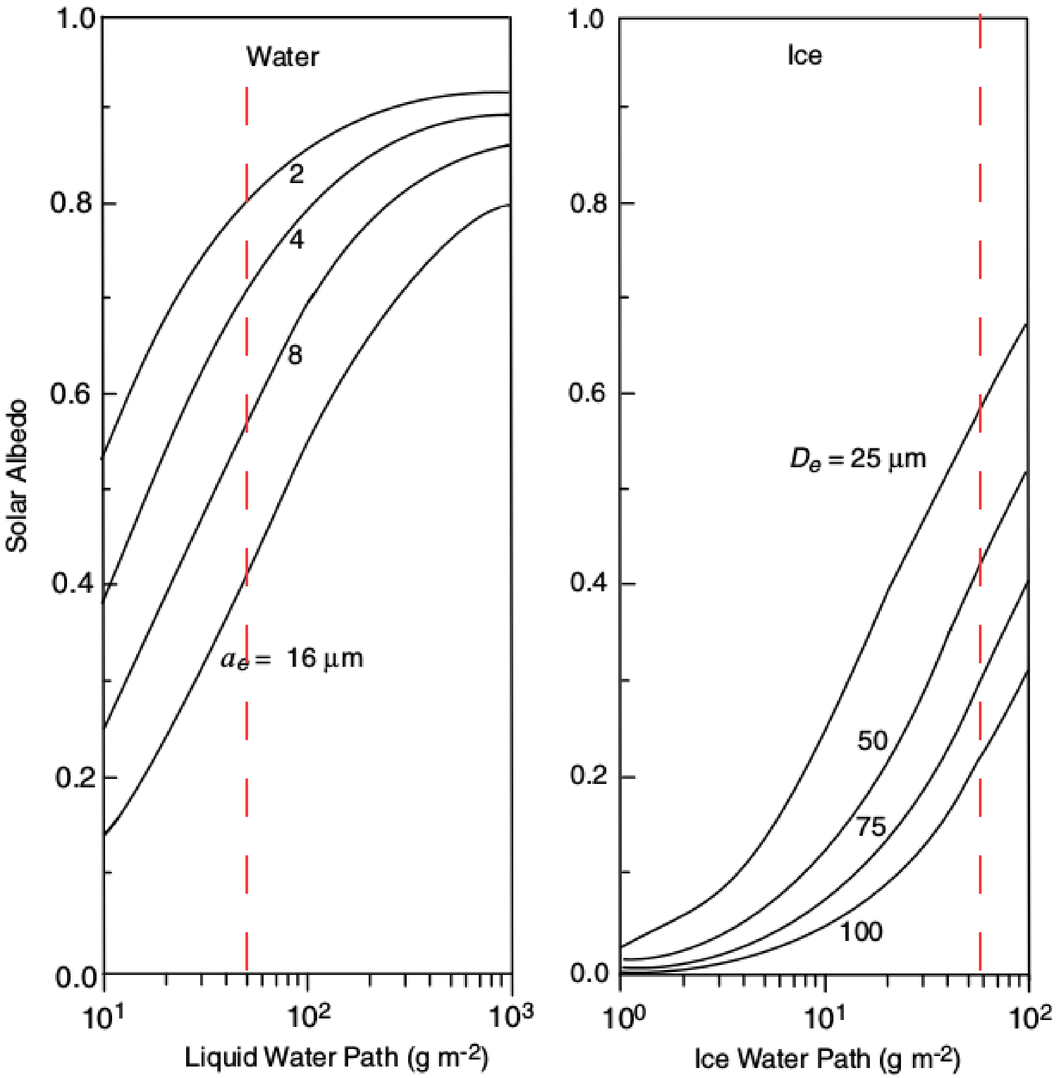
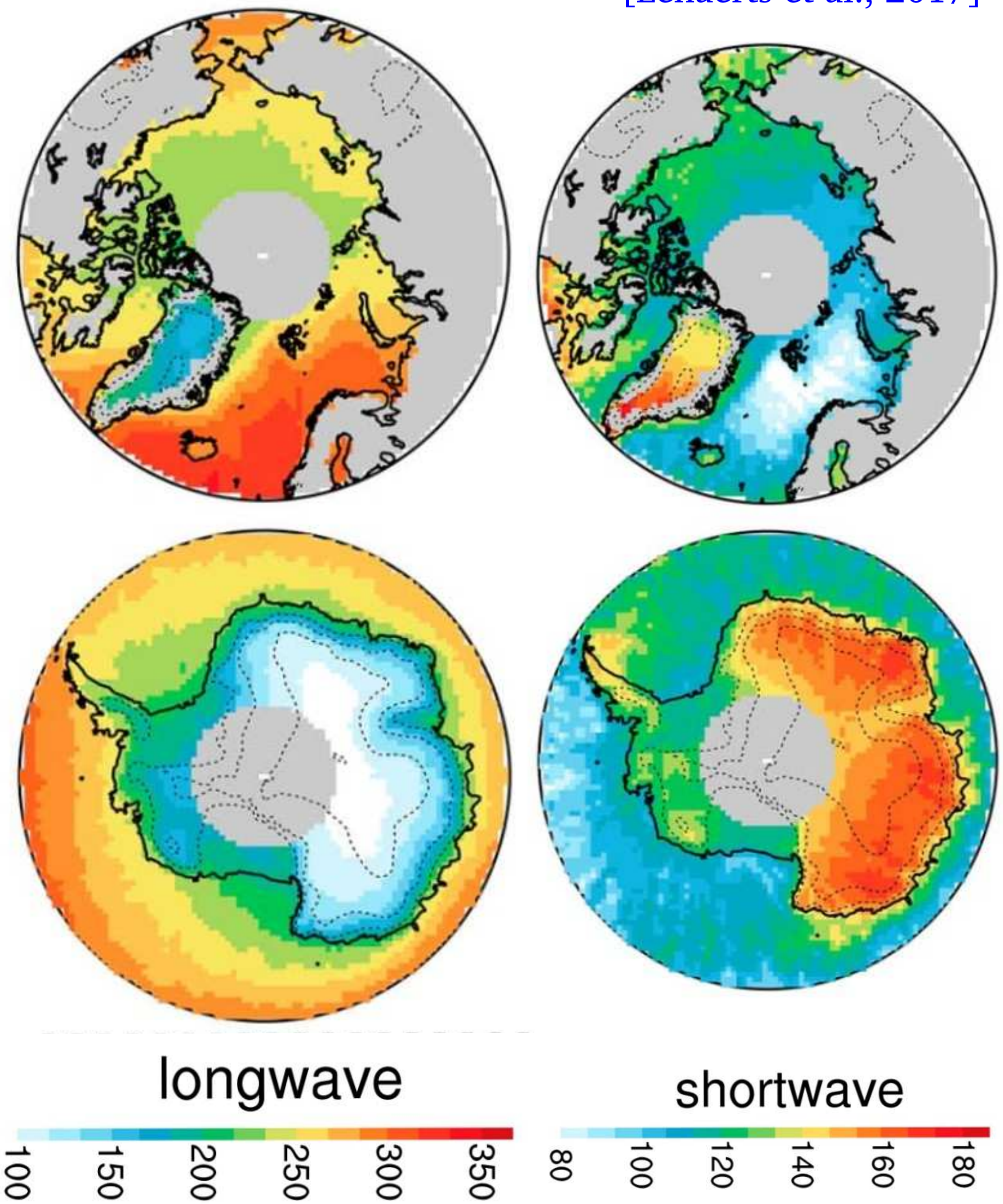
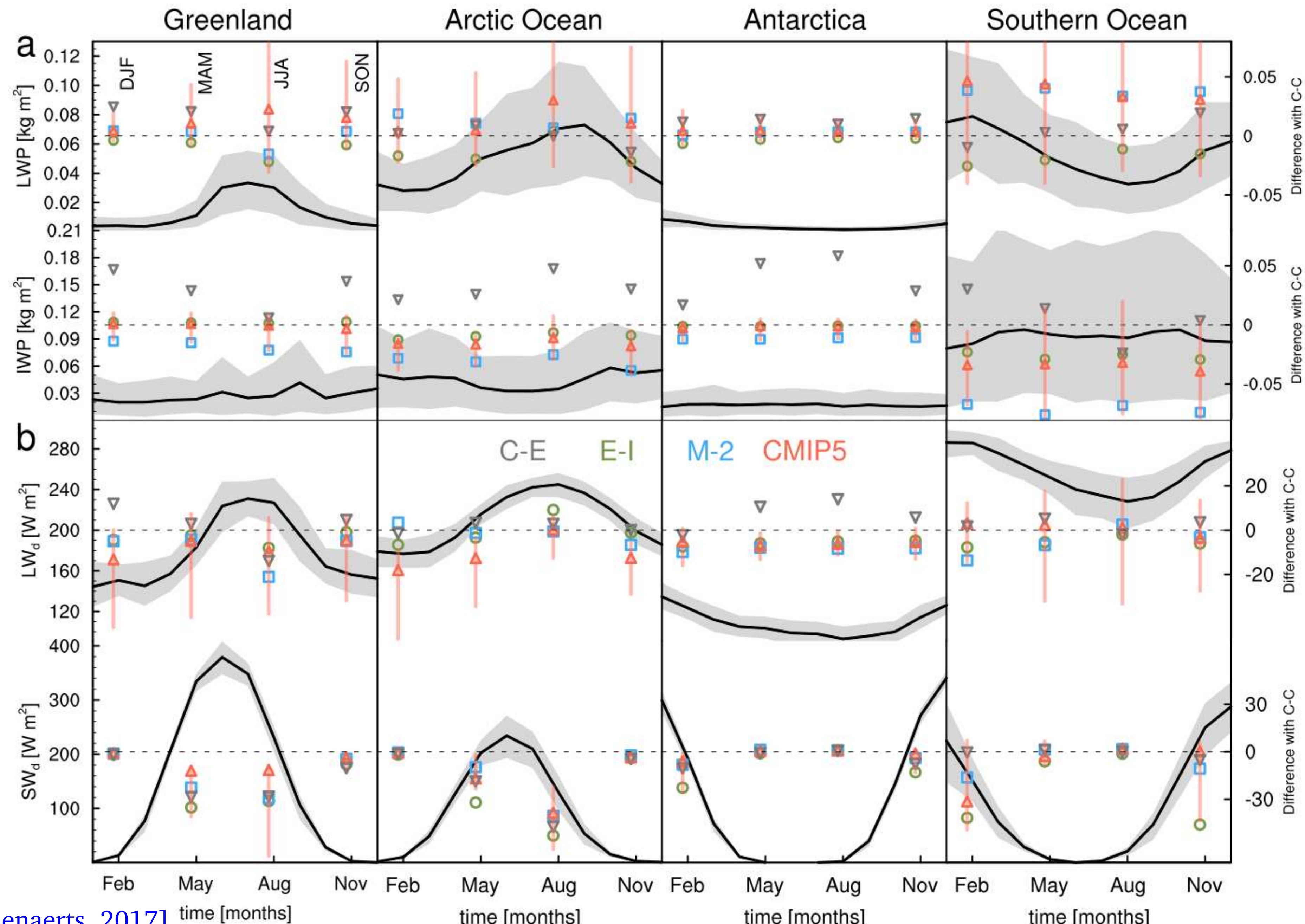
[Lenaerts et al., 2017]



[Liou 2002]



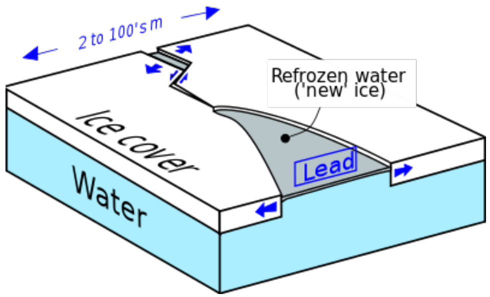
Annual evolution – clouds and surface fluxes



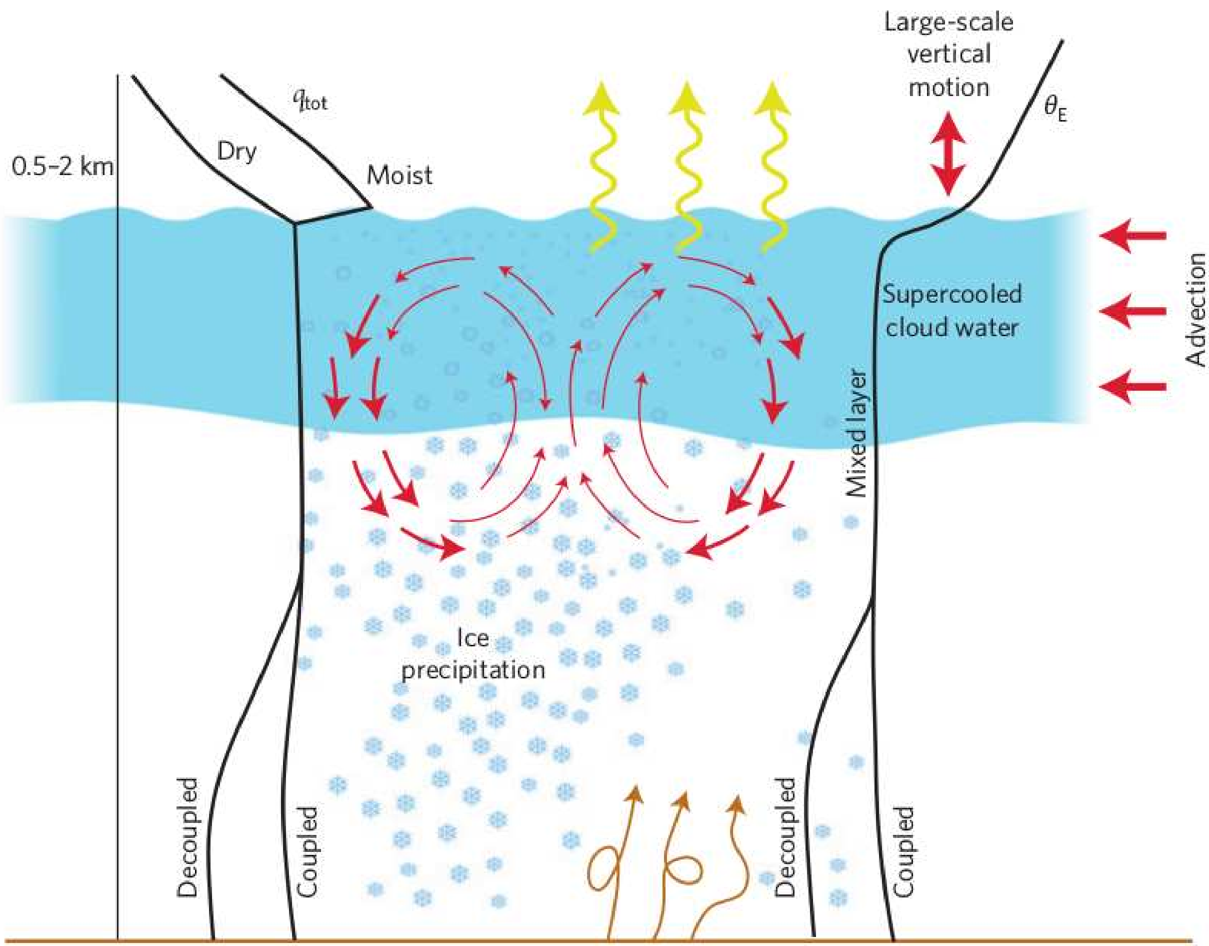
[Lenaerts, 2017]

Main polar cloud types

- Arctic :
  - Summertime stratus clouds
  - **Clear-sky ice crystal clouds** : ubiquitous at wintertime. Radiative cooling → growing of ice crystals → sedimentation
  - **Clouds associated with leads** : large temperature difference between air and water over leads in winter → convection → formation of ice clouds
- Antarctic :
  - **Coastal stratus clouds** → low-pressure systems reaching the coast
  - Cold-air outbreaks
  - **Ice-sheet cirrus clouds**, **altostratus** (oceanic air intrusions), and **summer cumulus clouds** (rare)
  - **Diamond dust**



Arctic summertime stratus clouds



[Morrison et al., 2011]

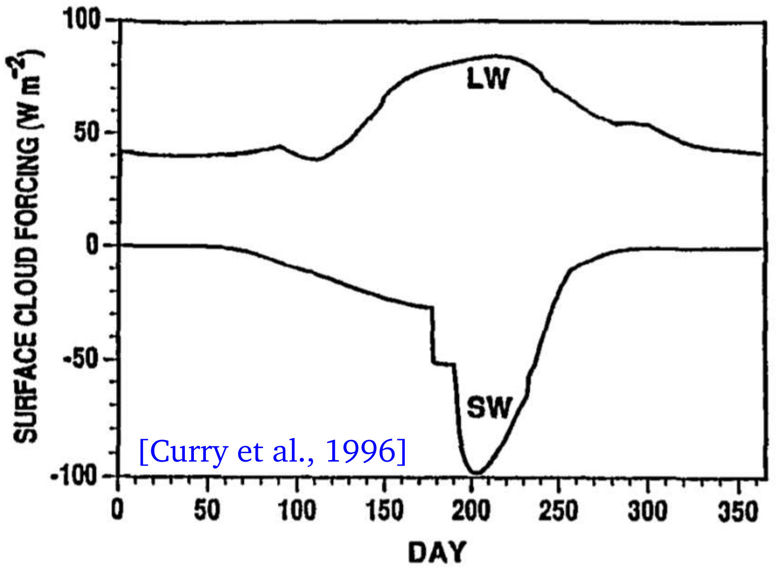
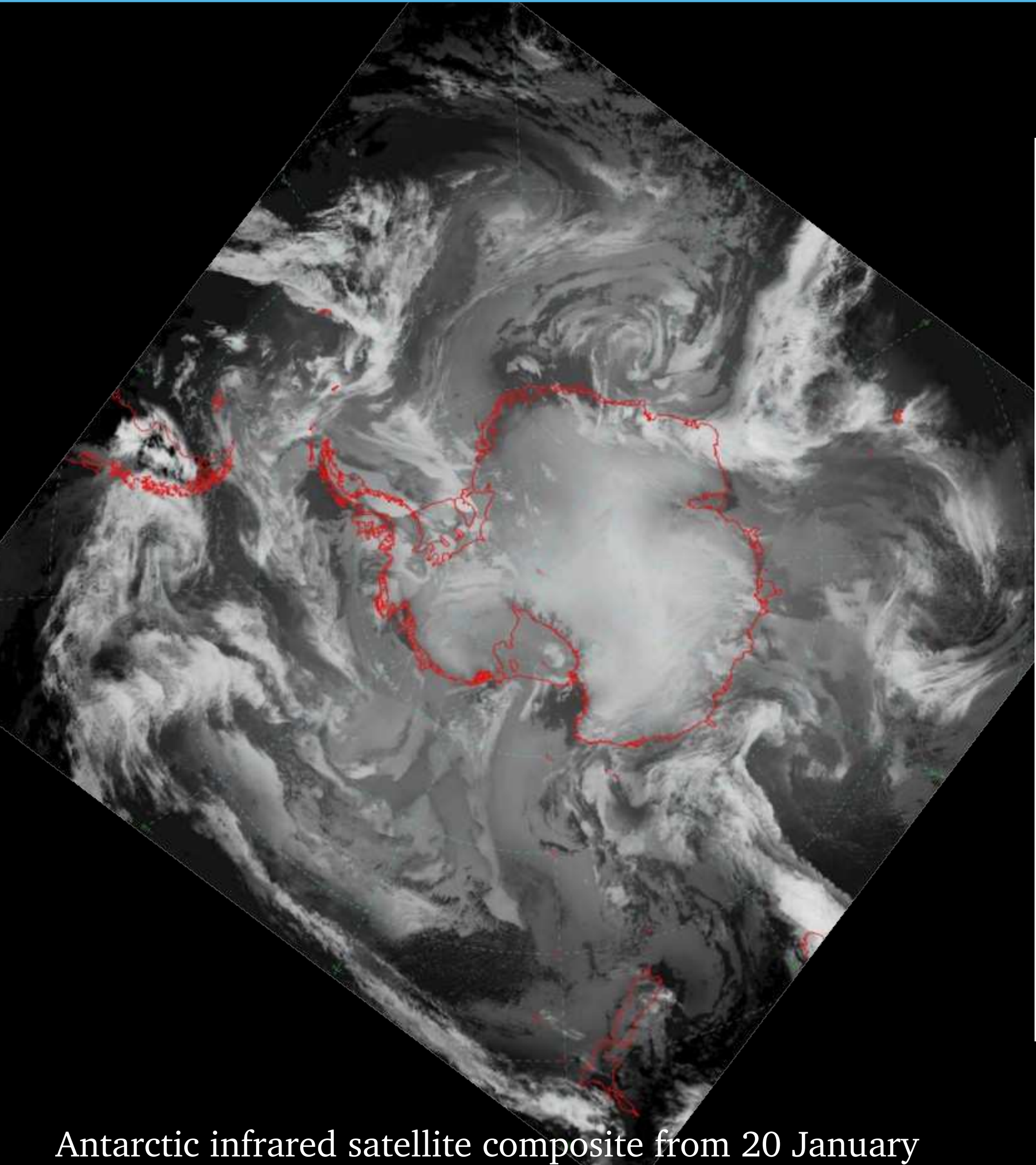


FIG. 9. Annual cycle of surface longwave and shortwave cloud forcing as determined by Curry and Ebert (1992) for 80°N.

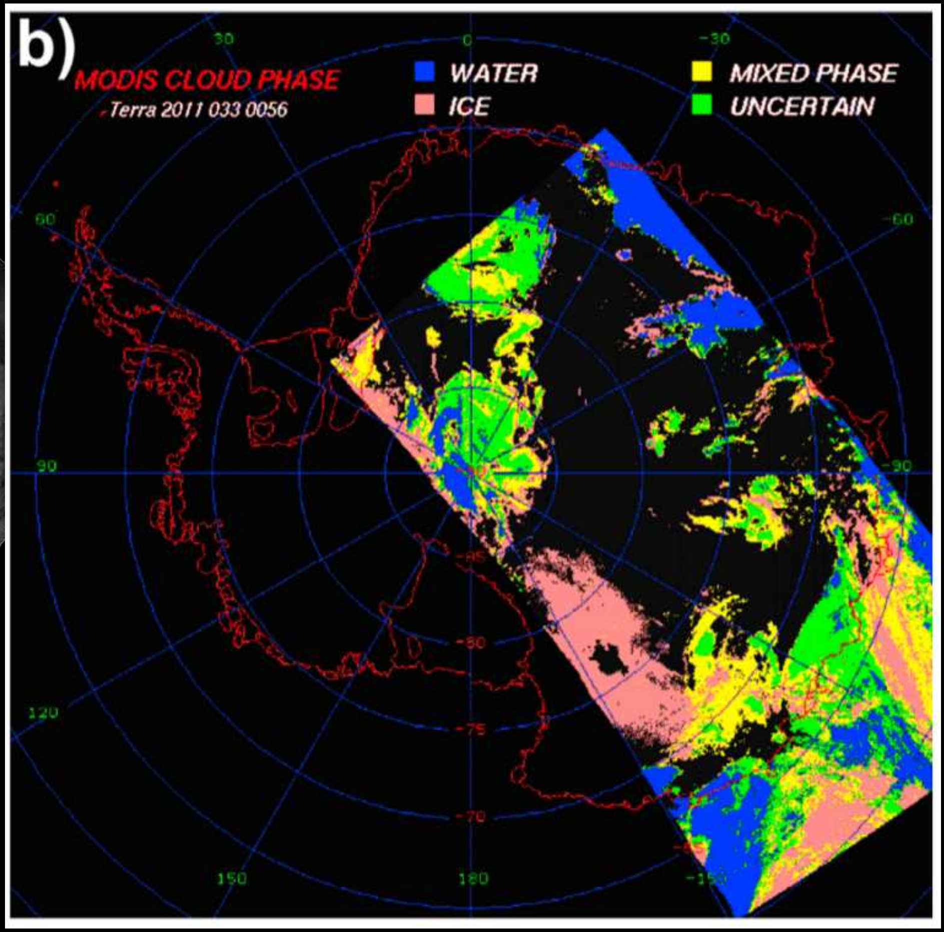
- Large scale advection of water vapor over sea ice → Cloud-top radiative cooling → Convection and vertical condensation growth of supercooled droplets → Bergeron effect and ice precipitation

- Humidity inversion at cloud-top → low dissipative effect of entrainment
- Most of the year, cloud radiative forcing is positive (warming effect)

Antarctic cold-air outbreaks



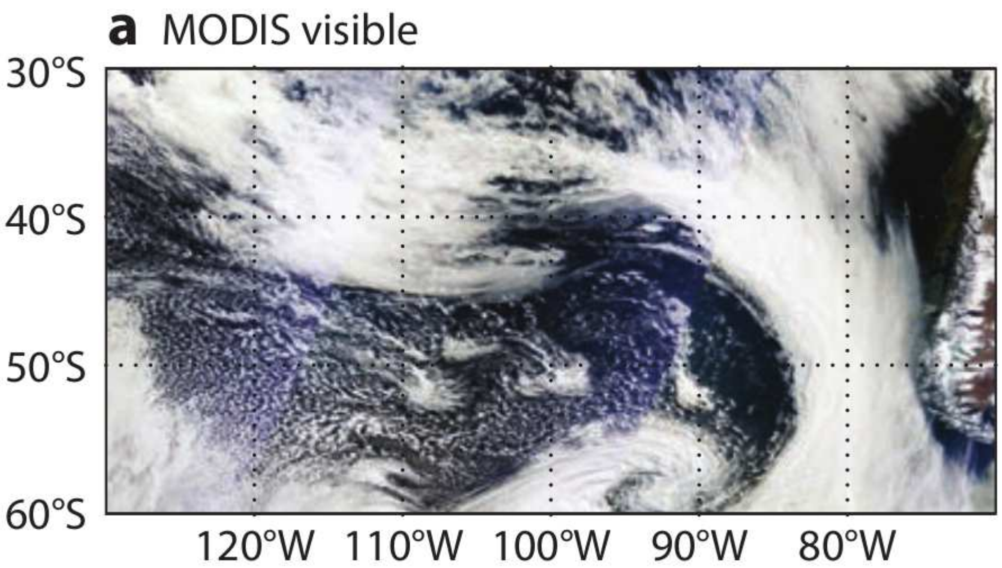
Antarctic infrared satellite composite from 20 January 2011 at 15:00 UTC showing clouds over the Antarctic and adjacent Southern Ocean. [AMRC/SSEC/UW-Madison]

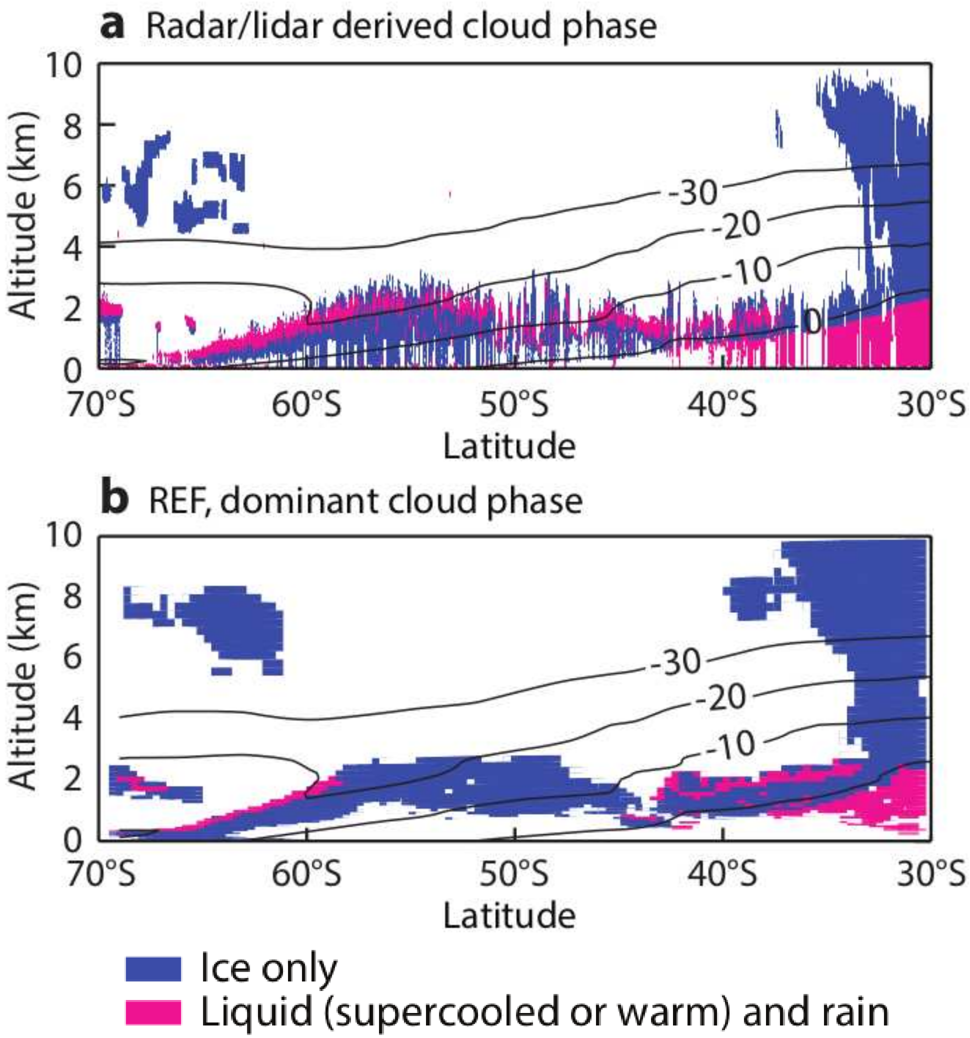


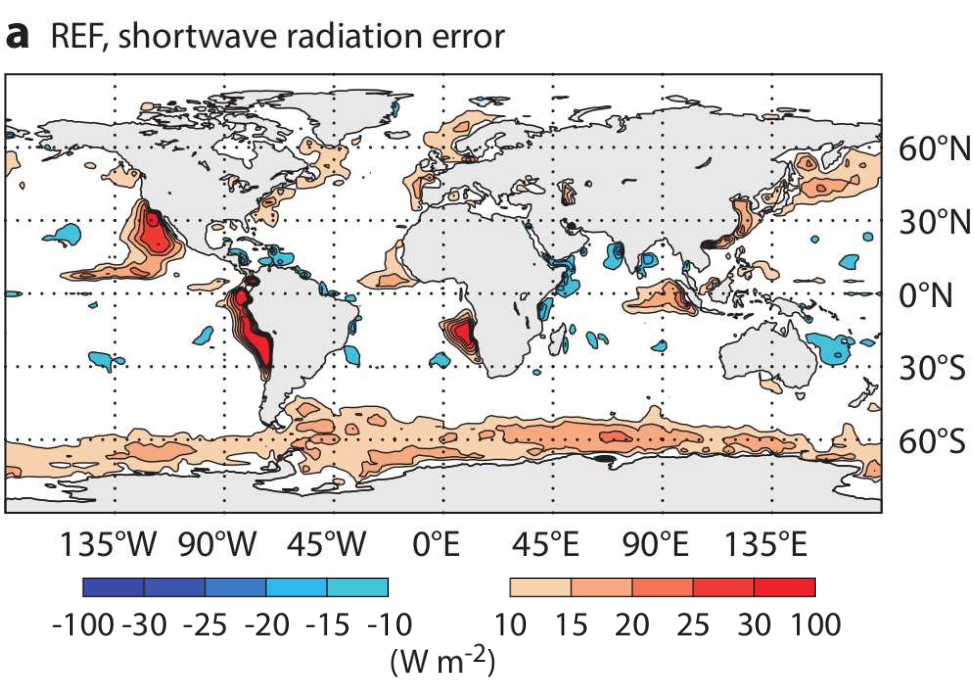
[Bromwich, 2012]

Animation roaring 40's

Antarctic cold-air outbreaks



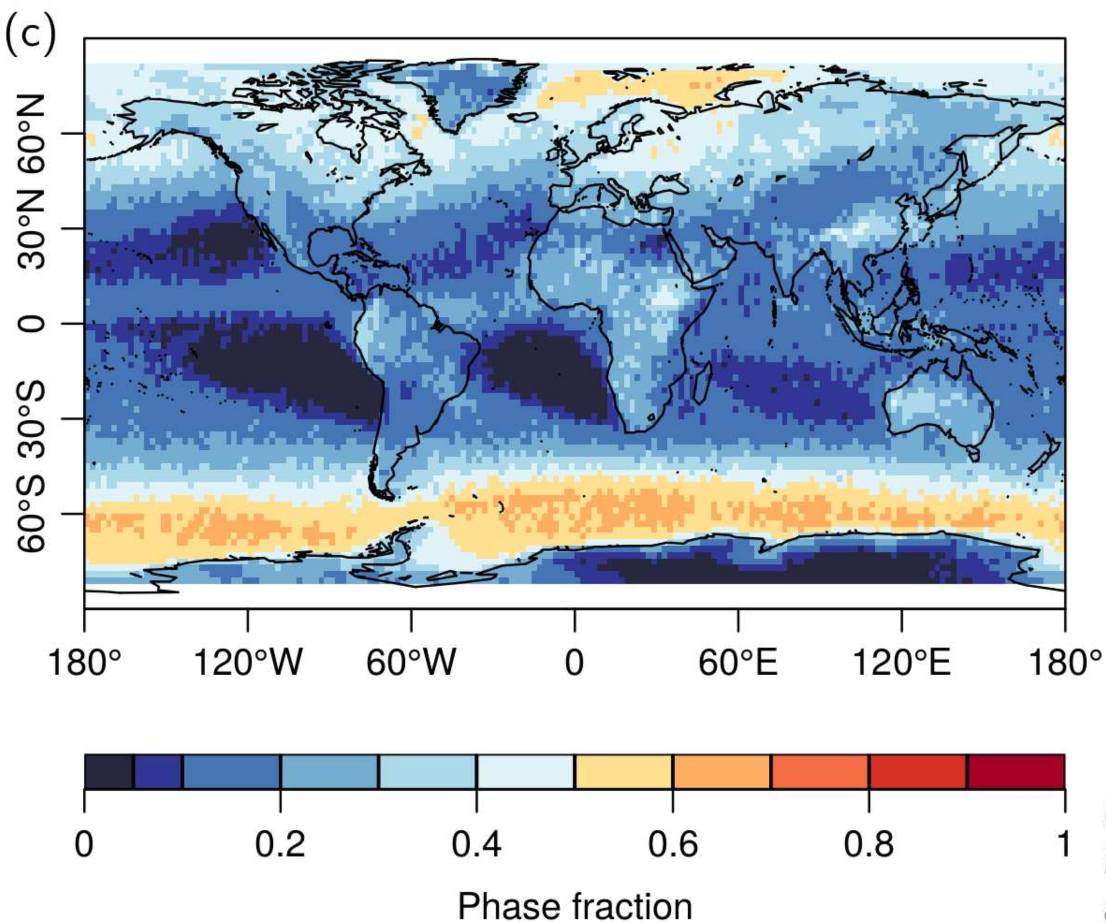




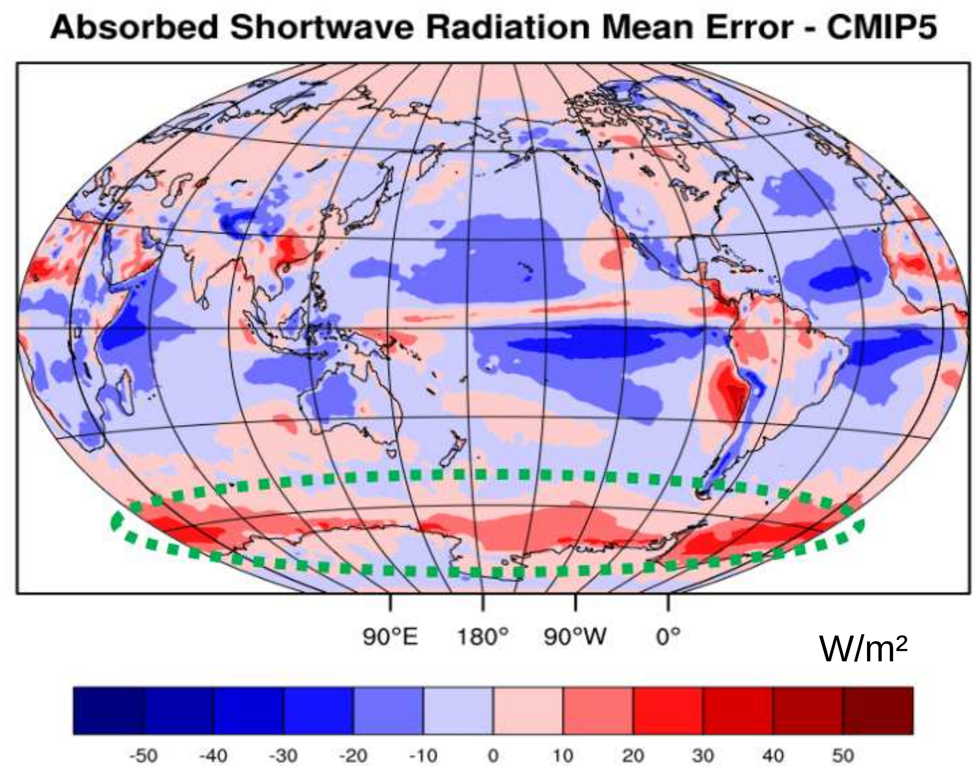
Cold air from Antarctica flowing over the warmer ocean → instability and convection → cloud formation

[Forbes et al., 2015]

Mixed clouds over the southern ocean



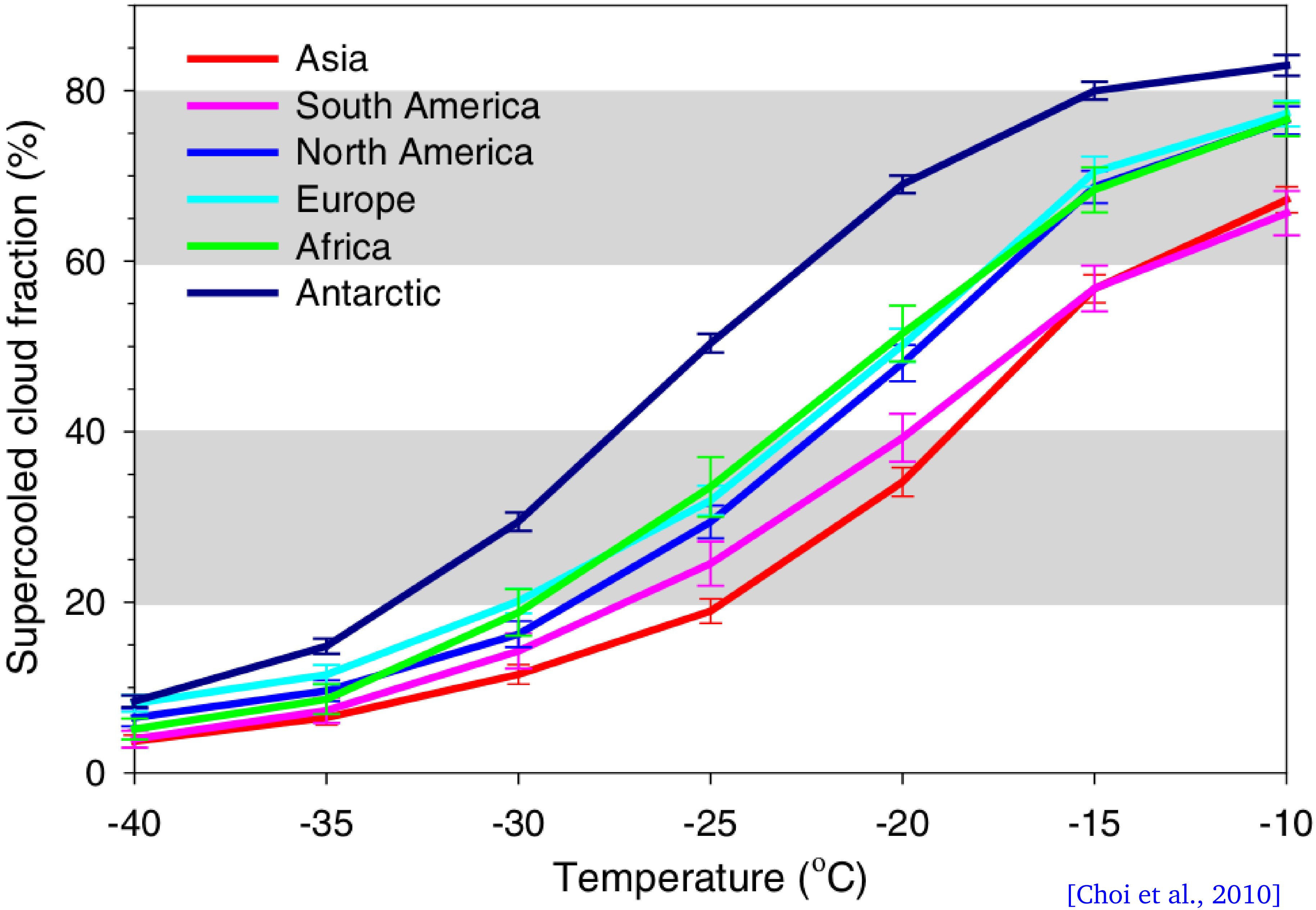
[Mulmenstadt et al., 2015]



CMIP5 model clouds do not reflect enough sunlight over SO. *Ensemble mean error for CMIP5 models in shortwave radiation absorbed by the Earth System. Positive values indicate too much shortwave radiation absorbed.*

[Ding et al., 2017, WAMC]

Observed phase as a function of temperature



[Choi et al., 2010]

Other antarctic clouds (Concordia, Dome C)

11h

16h

[J-B Madeleine]

Animation cirrus clouds

Modeling of polar clouds

	Modeling period			
	1960/70s	*1970/80s*	*1980/90s*	*Now and beyond*
Condensation (nonconvective)	$\bar{q} > \bar{q}_s$	$\bar{q} > \bar{q}_s$	*l* prognostic function of outcome of processes	*l* prognostic function of the processes themselves

(with l the condensate content)

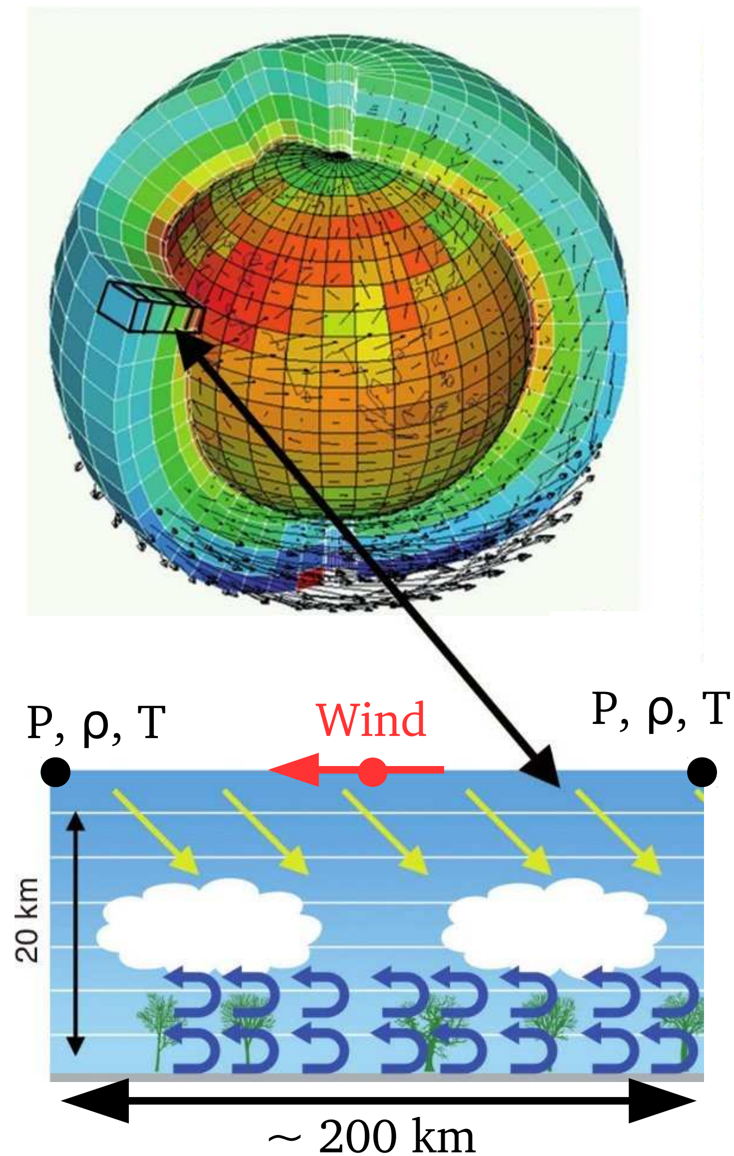
[Jakob & Miller, 2003]

- Separation is often made in GCMs between :
  - **Processes occurring on the model grid scale** (« macrophysics », « bulk microphysics ») ;
  - **Processes occurring on the sub-grid scale** (« physical parameterizations », which compute *the statistical effects on the grid box mean state of subgrid scale processes.* See for example the statistical cloud schemes developed for cumulus clouds).
- We also distinguish two main types of schemes :
  - **Diagnostic cloud schemes :** cloud parameters (cloud fraction, amount, particle sizes) are diagnosed using the grid-averaged quantities (example : cloud fraction is often parameterized as a function of RH)
  - **Prognostic cloud schemes :** the time evolution of the cloud condensate and cloud fraction are described using prognostic equations →

(where A=advection, S=source, D=dissipation/sink)

$$\frac{\partial l}{\partial t} = A(l) + S(l) - D(l)$$

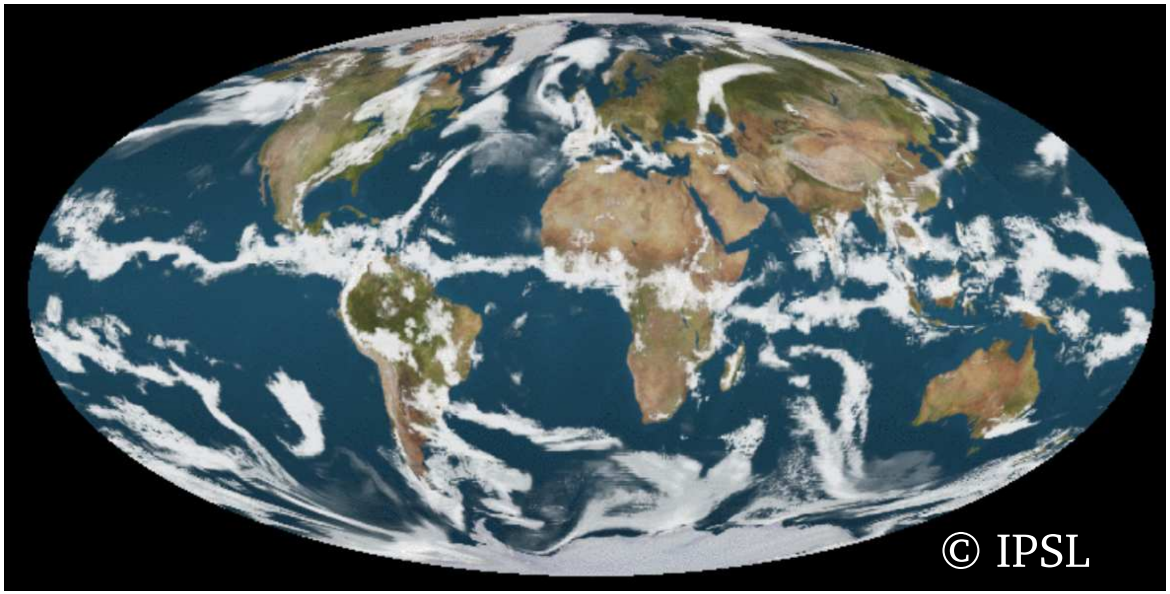
IPSL Climate Model



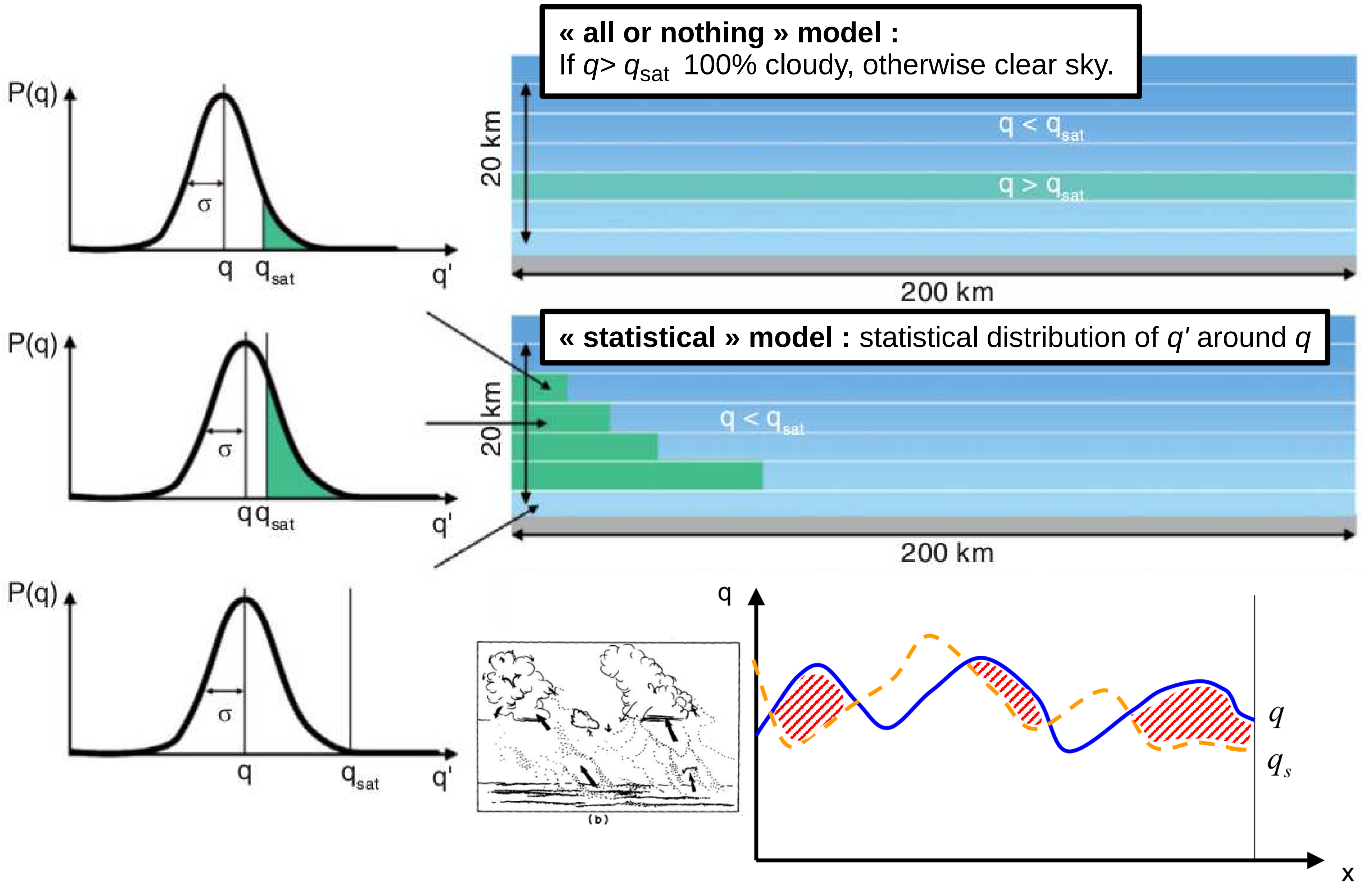
→ **Dynamical "core"**
Primitive hydrostatic equations of meteorology

→ **Radiative transfer model**
RT equations (plane-parallel approximation)

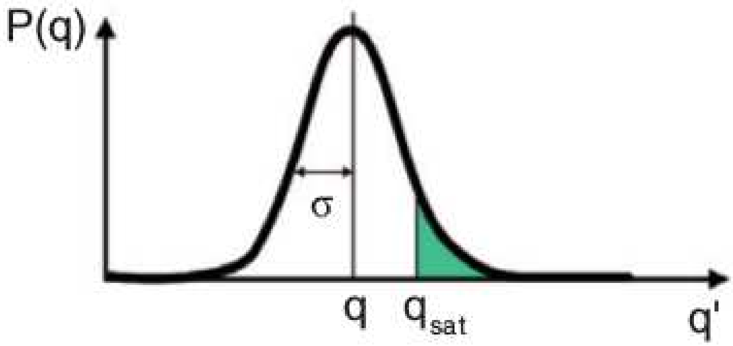
→ **Physical "parameterizations"**
Processes not resolved by the model grid (turbulence, clouds and precipitation, convection)

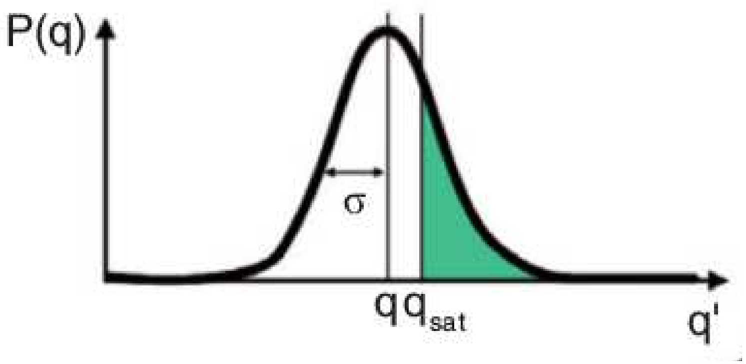


Statistical cloud scheme



Statistical cloud scheme : basic equations





The goal of a cloud scheme is to compute **the in-cloud water content q_c^{in} and cloud fraction** based on different physical parameterizations

Mean total water content :

$$\bar{q} = \int_0^{\infty} q \; P(q) \; dq$$

Domain-averaged amount of condensate :

$$q_c = \int_{q_{sat}}^{\infty} (q - q_{sat}) P(q) dq$$

Cloud fraction :

$$\alpha_c = \int_{q_{sat}}^{\infty} P(q) dq$$

In-cloud condensed water content :

$$q_c^{in} = \frac{q_c}{\alpha_c}$$

Bi-gaussian PDF for shallow convective clouds

Bi-Gaussian distribution of saturation deficit s:

$$S = a_l\,(q_t - q_{sat}(T))$$

- One mode associated with thermals s_{th}, σ_{th}
- One mode associated with their environment: s_{env}, σ_{env}

We know:
Mean state: s_{env}
Thermal properties: s_{th}, α

Parameterization of the variances:

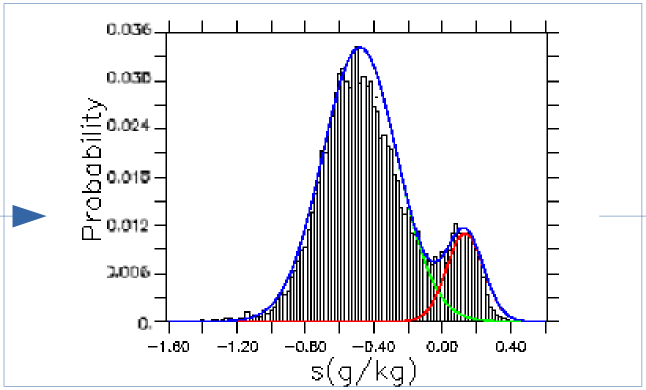
$$\sigma_{s,\mathrm{th}} = c_{\mathrm{th}}\,\alpha^{-\frac{1}{2}}\,(\overline{s}_{\mathrm{th}} - \overline{s}_{\mathrm{env}}) + b\,\overline{q}_{t_{\mathrm{th}}}$$

$$\sigma_{s,\mathrm{env}} = c_{\mathrm{env}}\,\frac{\alpha^{\frac{1}{2}}}{1-\alpha}\,(\overline{s}_{\mathrm{th}} - \overline{s}_{\mathrm{env}}) + b\,\overline{q}_{t_{\mathrm{env}}}$$

q_c^{in} is deduced from the mean water content of the environment and thermals and the parameterized spreads of the two gaussian distributions

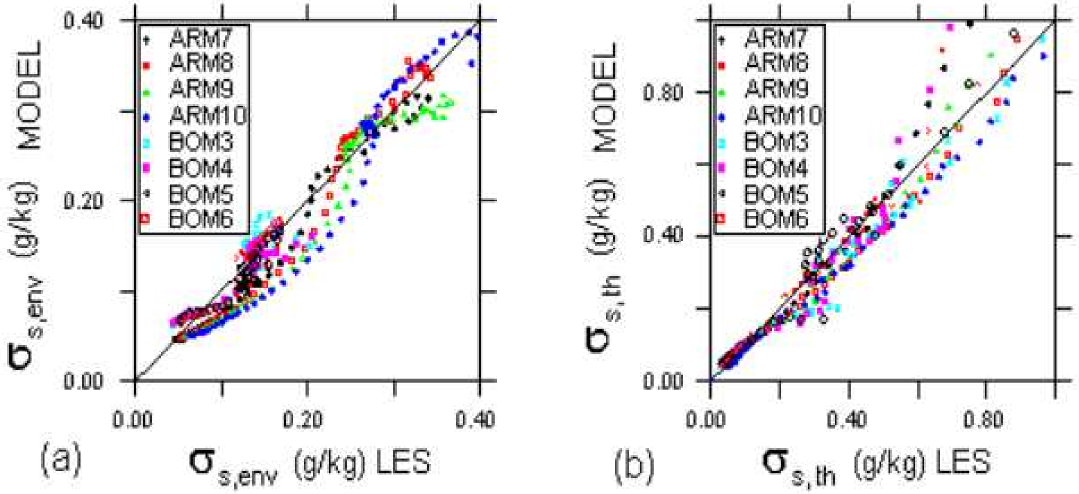
Shallow convection

s_{env}, σ_{env}
s_{th}, σ_{th}, α



q_c, cf

[Jam et al., BLM, 2012]

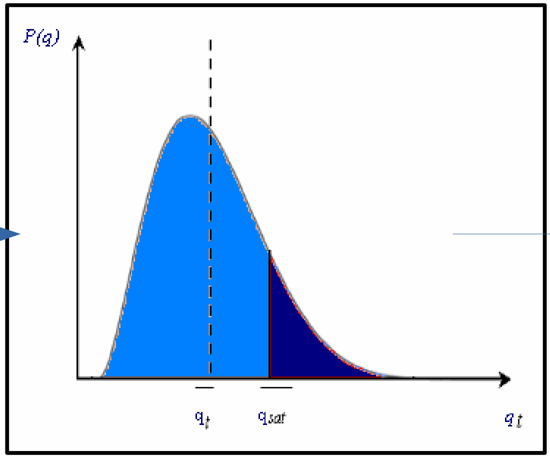


Large-scale condensation scheme

Log-normal distribution of total water q_t [Bony & Emanuel, 2001]

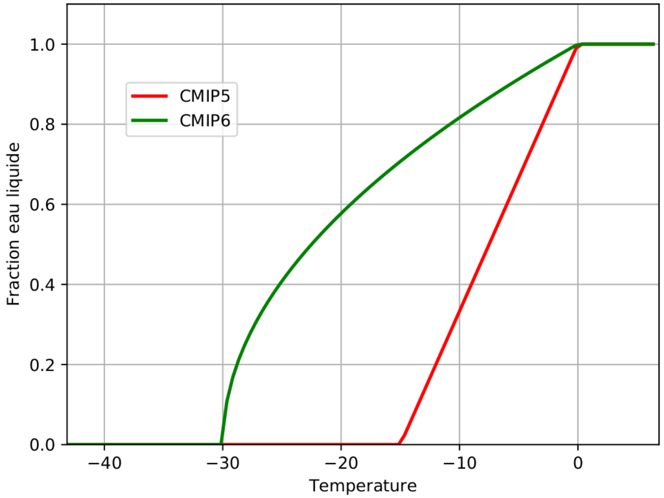
Grid-cell mean state → q, q_{sat}

σ/q imposed



$$\alpha_c = \int_{q_{sat}}^{\infty} P(q)dq$$

$$q_c = \int_{q_{sat}}^{\infty} (q - q_{sat})P(q)dq$$



- condensate: liquid/ice partitioning (function of the temperature) :

$$^{a}\text{Cloud liquid fraction} = \left(\frac{T - T_{min}}{T_{max} - T_{min}}\right)^n, \text{ for } T_{min} \le T \le T_{max}$$

- A fraction of the condensate falls as rain (parameters controlling the maximum water content of clouds and the auto-conversion rate) :

$$\frac{dq_{lw}}{dt} = -\frac{q_{lw}}{\tau_{convers}}\left[1 - e^{-(q_{lw}/clw)^2}\right]$$

$$\frac{dq_{iw}}{dt} = \frac{1}{\rho}\frac{\partial}{\partial z}(\rho w_{iw} q_{iw})$$

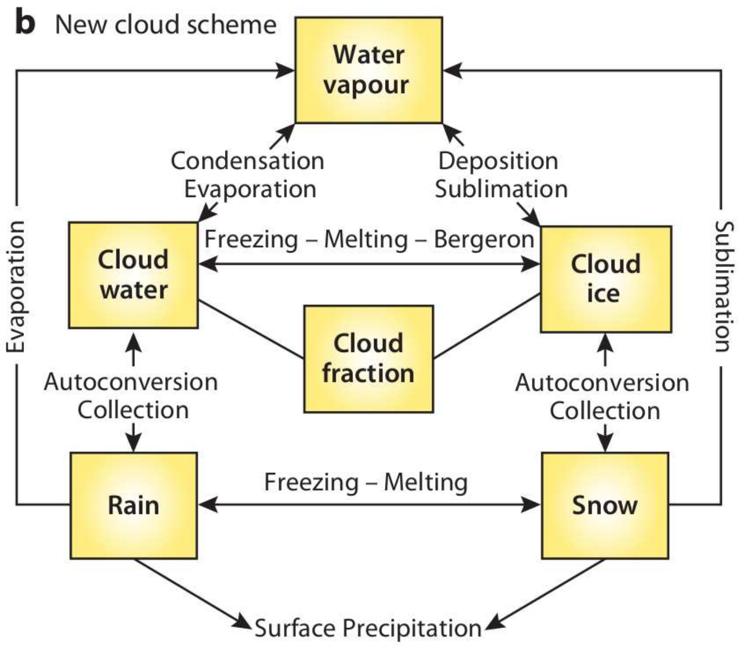
$$w_{iw} = \gamma_{iw} w_0$$

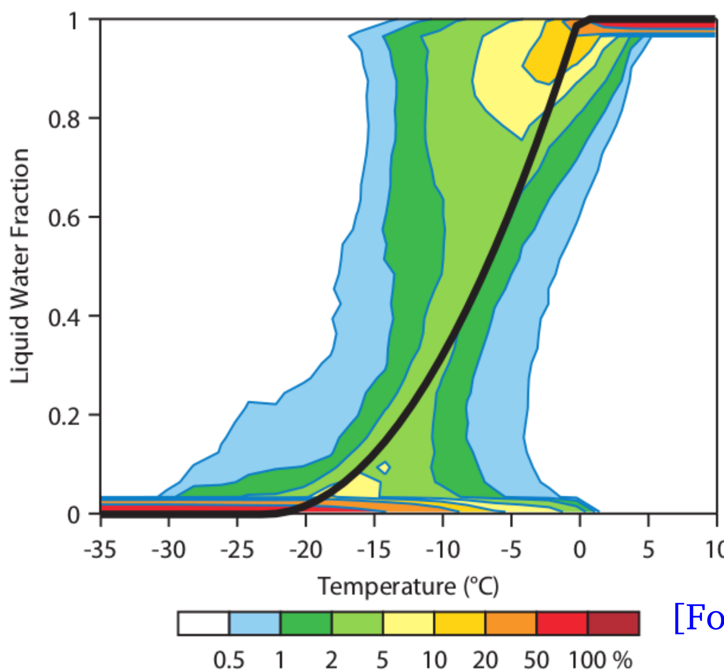
$$w_0 = 3.29(\rho q_{iw})^{0.16}$$

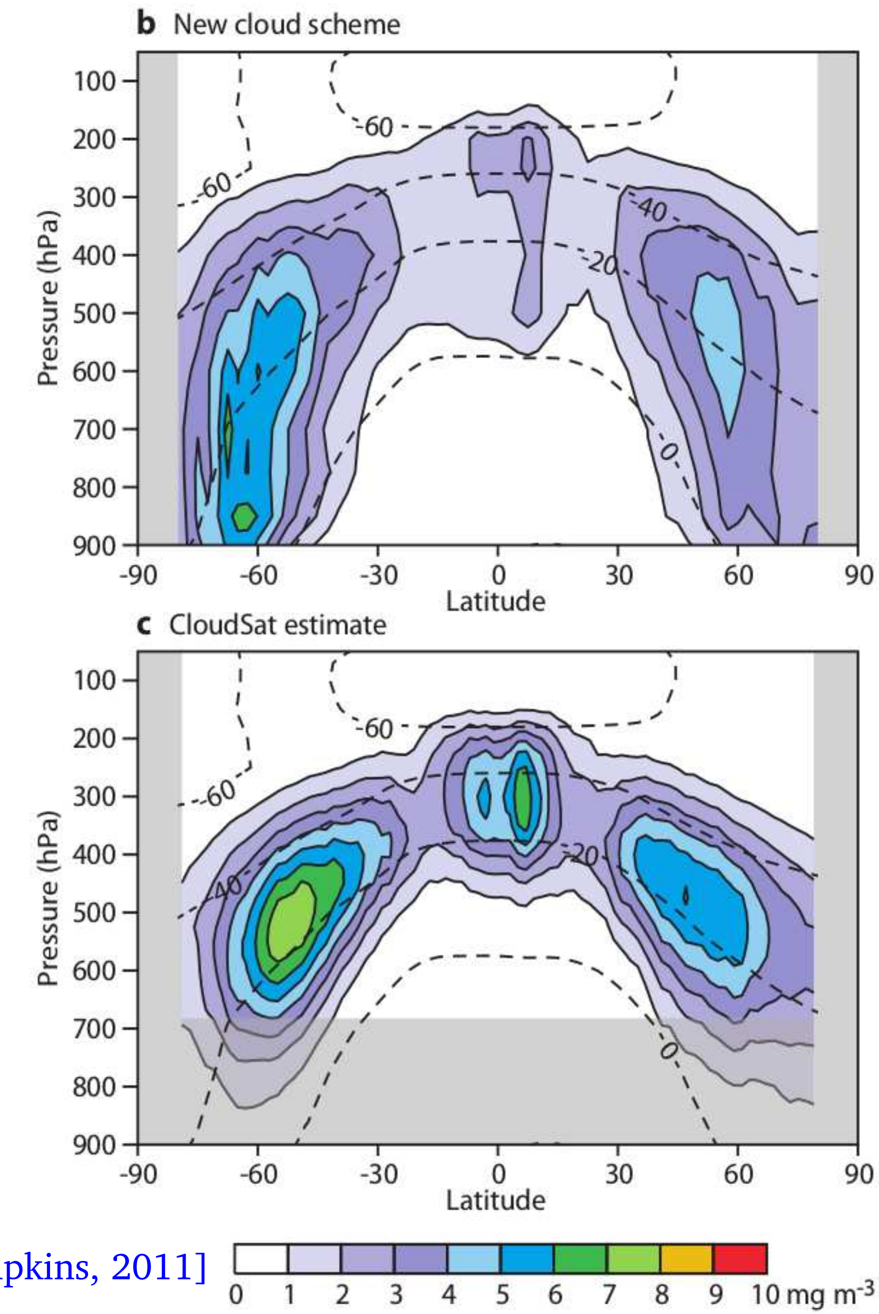
- The rain is partly evaporated in the grid below (parameter controlling the evaporation rate) :

$$\frac{\partial P}{\partial z} = \beta[1 - q/q_{sat}]\sqrt{P}$$

More complex schemes : ECMWF IFS (Cy41r1)

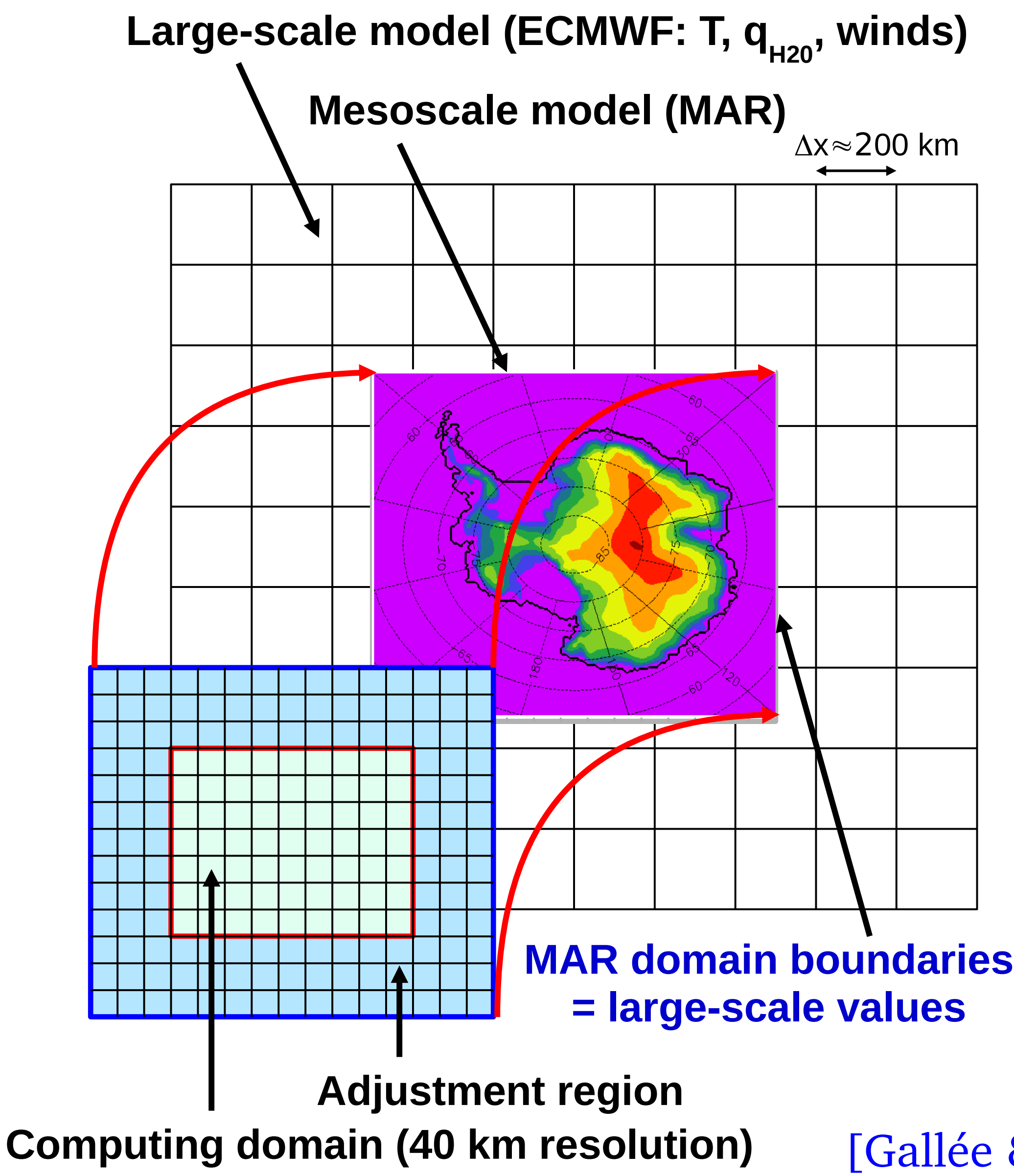






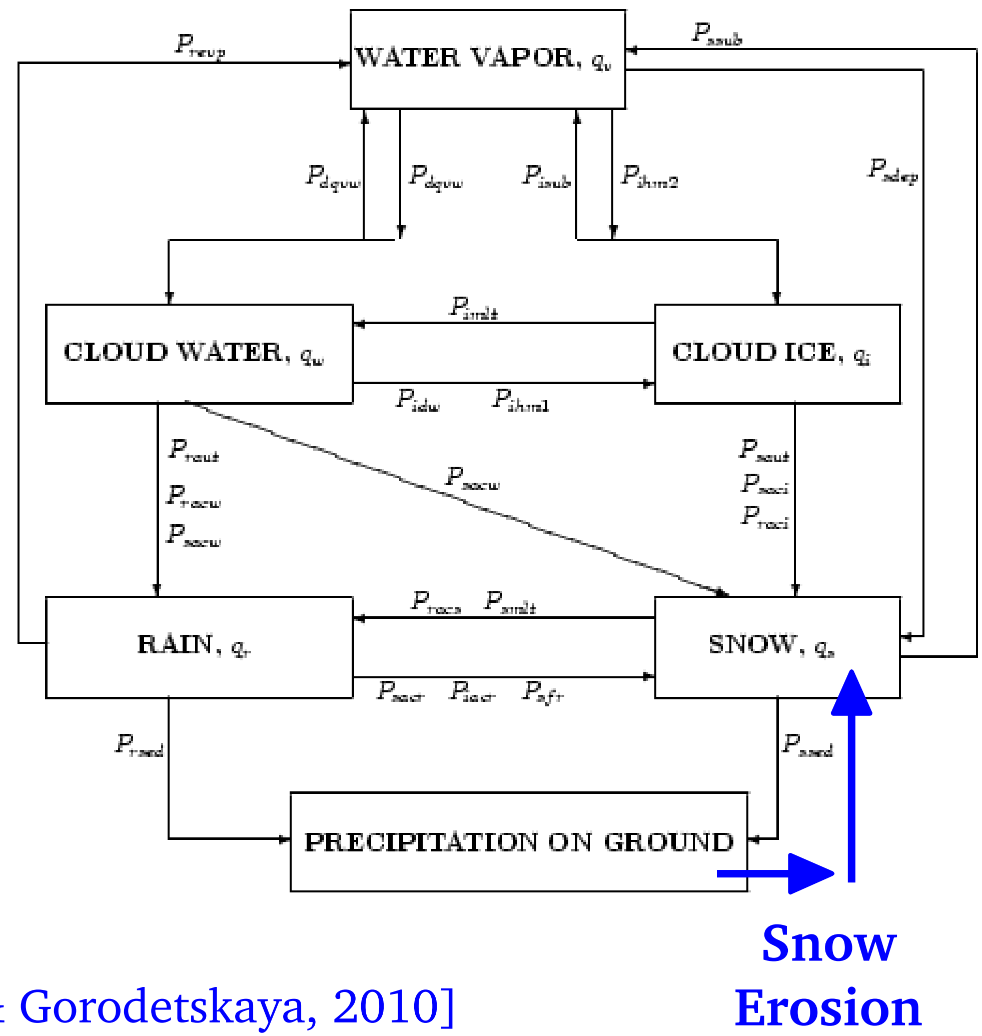
[Forbes & Tompkins, 2011]

MAR (Modèle Atmosphérique Régional)



Microphysics scheme

(6 pronostic equations)

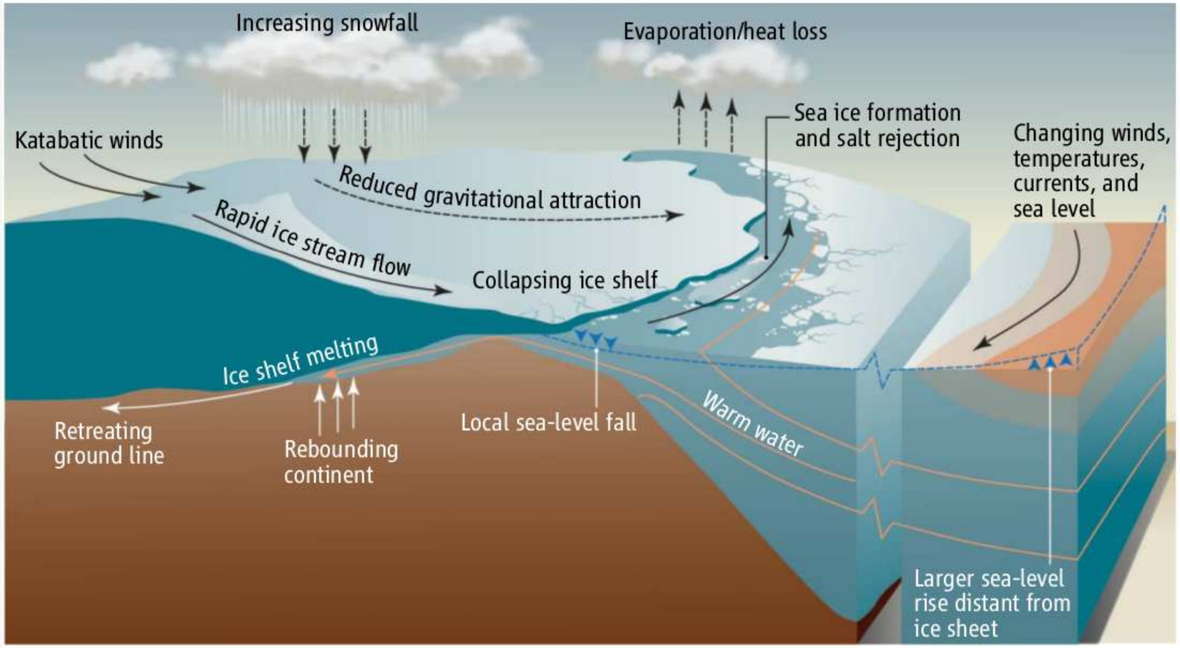


[Gallée & Gorodetskaya, 2010]
Appendix of Gallée [1995]

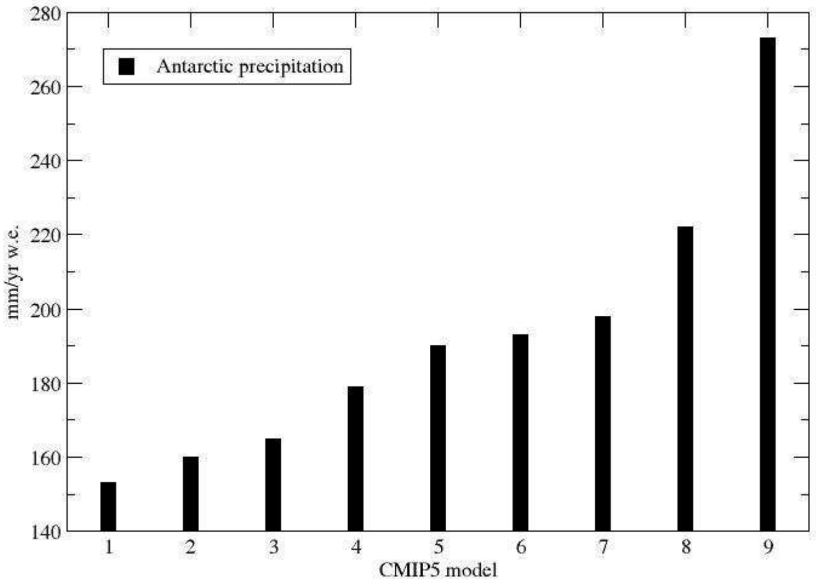
Conclusion

Understanding and predicting the future evolution of polar clouds is crucial :

- **In the Arctic**, where sea-ice evolution is strongly dependent on clouds and their LW effect ;
- **In the Antarctic** :
  - Sea-surface temperatures are strongly dependent on mixed-phase clouds in the southern ocean ;
  - Snowfall and the long-term evolution of the ice-sheet also depends on future cloud properties.



[Willis & Church, 2012]



[adapted from Palerme et al., 2014]

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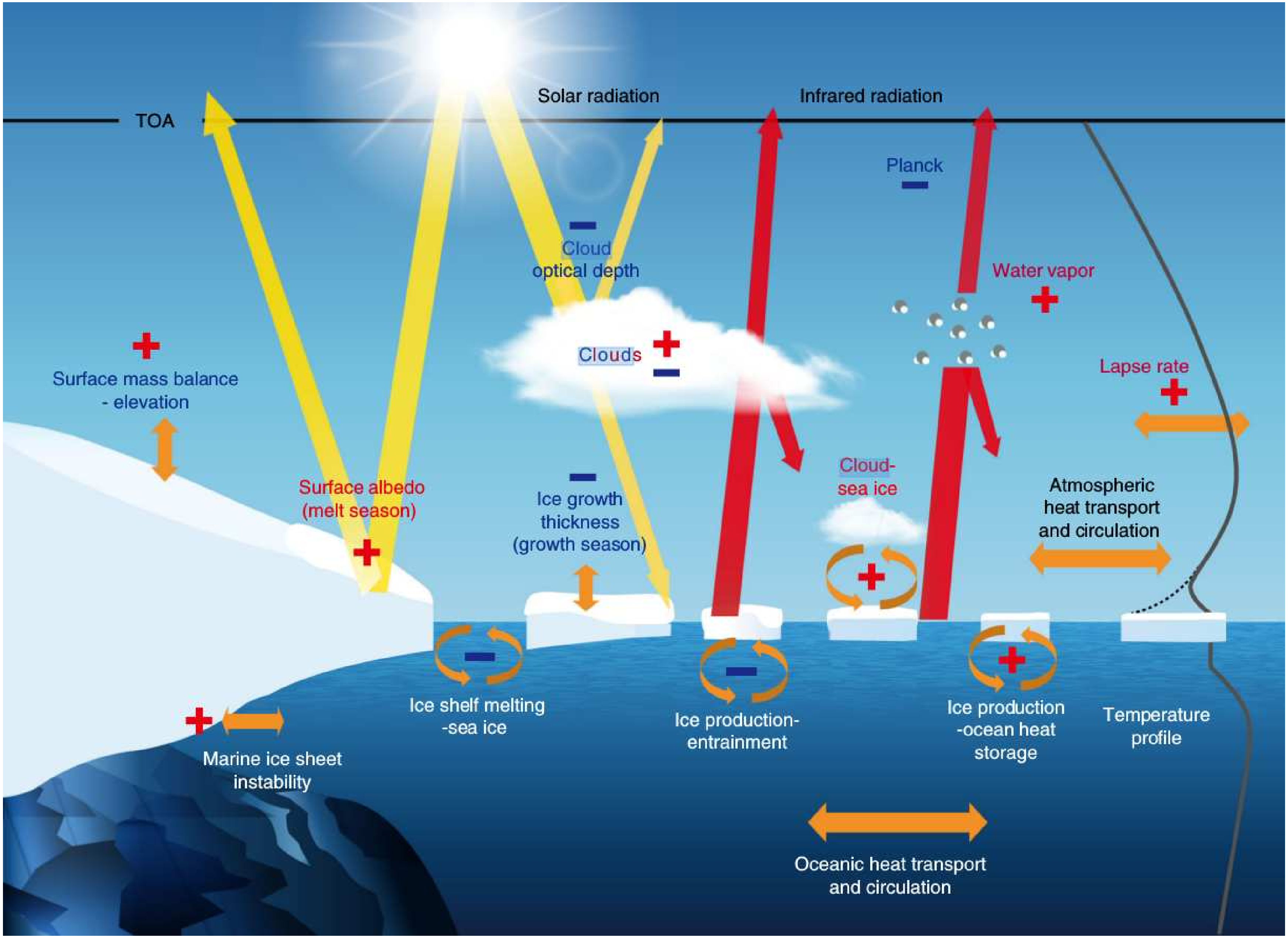
Polar feedbacks



[Goosse et al., 2018]