Modeling Studies of Primary and Secondary Ice Production in Arctic Mixed-Phase Clouds

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Arctic Mixed-Phase Clouds

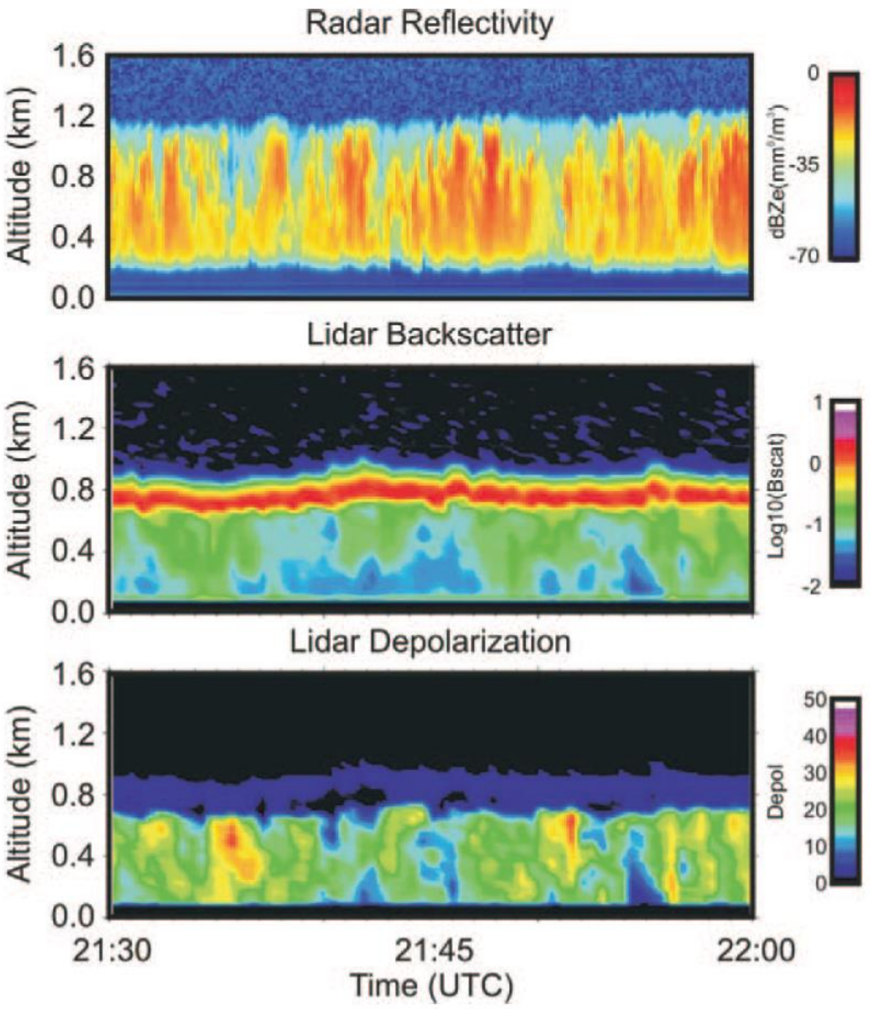


Fig. 6. PARSL (top) radar reflectivity, (middle) lidar backscatter, and (bottom) depolarization for the UND Citation overflight on 10 Oct 2004.

Verlinde et al. 2007

This is an example of Arctic mixed-phase cloud observed in the M-PACE field experiment, 2004.

--- Layer of liquid droplets (200-300 m thick):
Longwave cooling drives boundary layer turbulence.

--- Ice particles:
Form in the liquid layer, and keep falling out of cloud base.

--- Mixed-phase can exist for several days.
From the microphysical point of view, we need to explain why the cloud maintains mixed-phase for such a long time.

We investigate:

--- Why there is continuous ice production in this kind of clouds;

--- How the primary and secondary ice processes contribute to ice production;

--- Why the cloud does not glaciate.

Primary Ice production in mixed-phase clouds

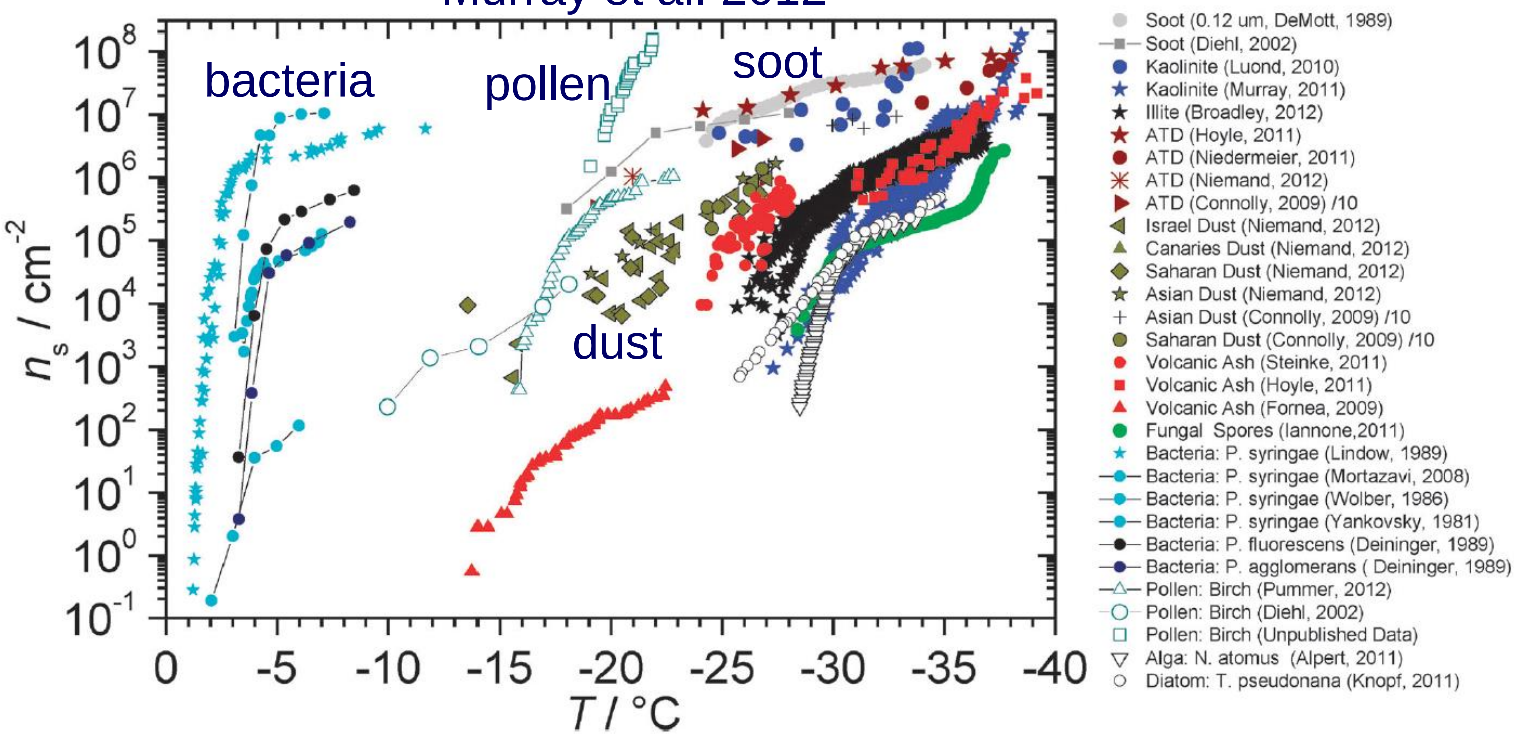
--- Ice-nucleating aerosols are needed:

Natural sources:
(1) Biological aerosols
such as bacteria and pollens;
(2) Dust;

Anthropogenic sources:
(3) Soot;
(4) Secondary organic aerosols.

--- In classical nucleation theory, each type corresponds to a contact angle (usually 30°~60° in models).

Murray et al. 2012



--- More efficient IN can initiate ice nucleation at higher temperature while less efficient IN only works at lower temperature.

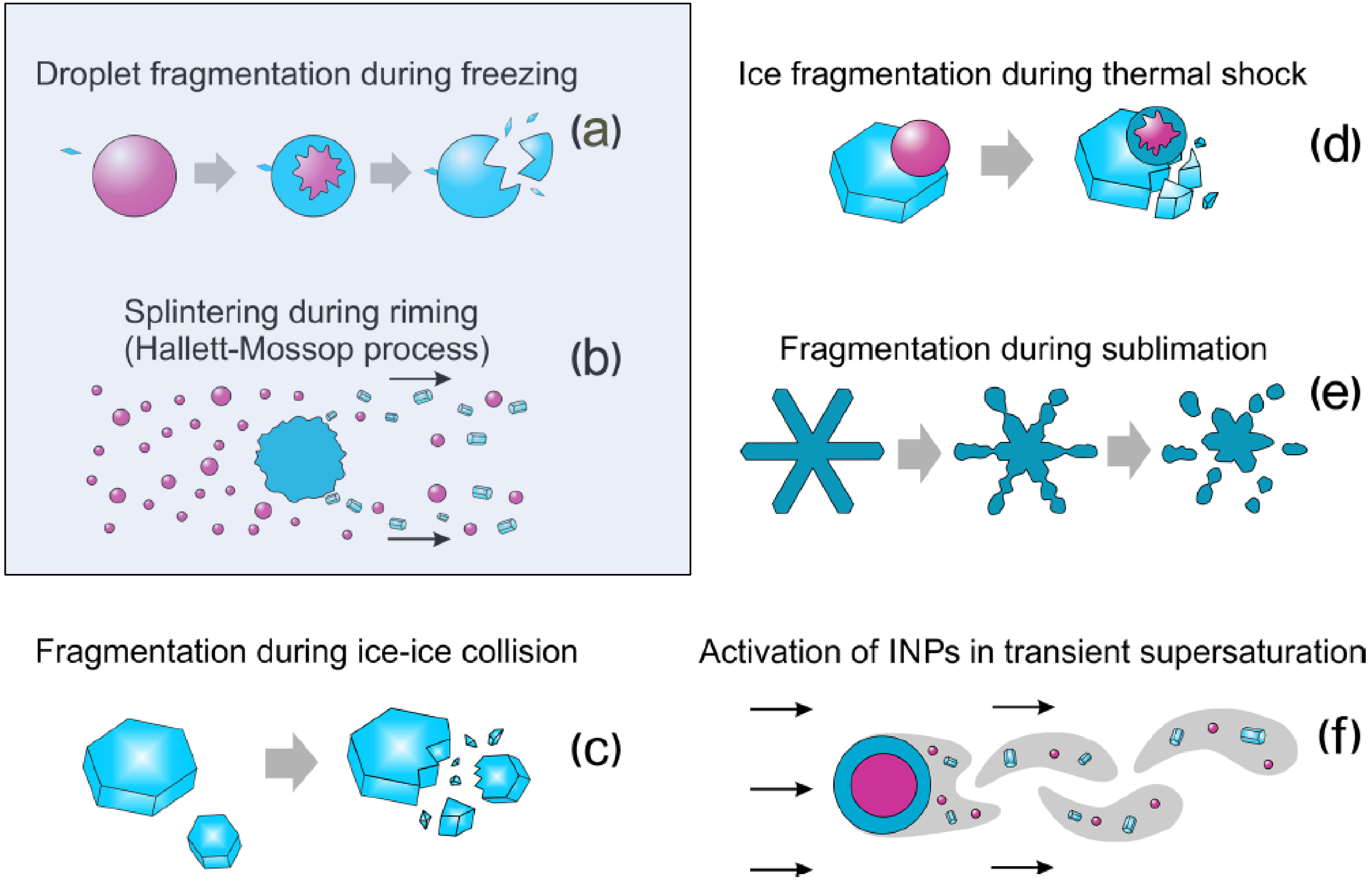
Each type also has a varying number concentration, depending on the location and time.
We focus on cloud responses to both the number concentration and efficiency of ice nuclei.

Secondary Ice production in mixed-phase clouds

-10 ~ -15 °C or wider T range

-3 ~ -8 °C

We only focus on (a) droplet freezing shattering because the selected case has a cloud base temperature of -10 °C.



Korolev and Leisner 2020

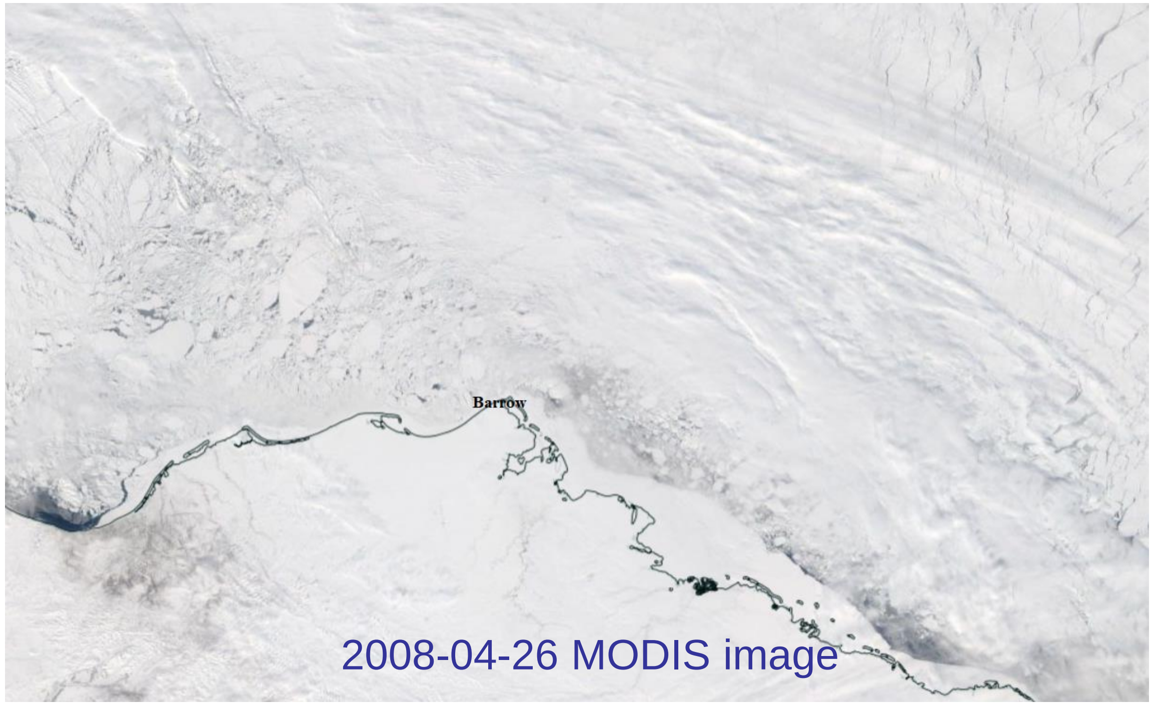
The Two Cases

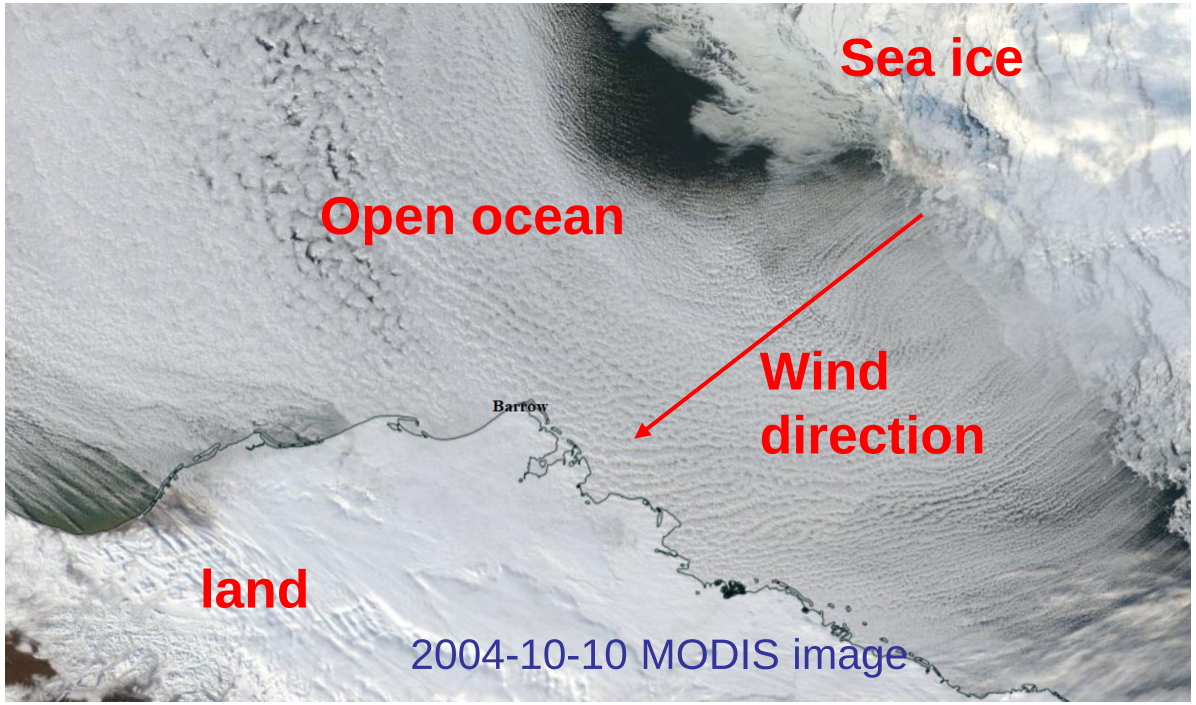
ISDAC case:

--- Spring time (April 2008)
--- The sea is covered by ice
--- Weak surface fluxes
--- Mainly driven by cloud-top longwave cooling.

M-PACE case:

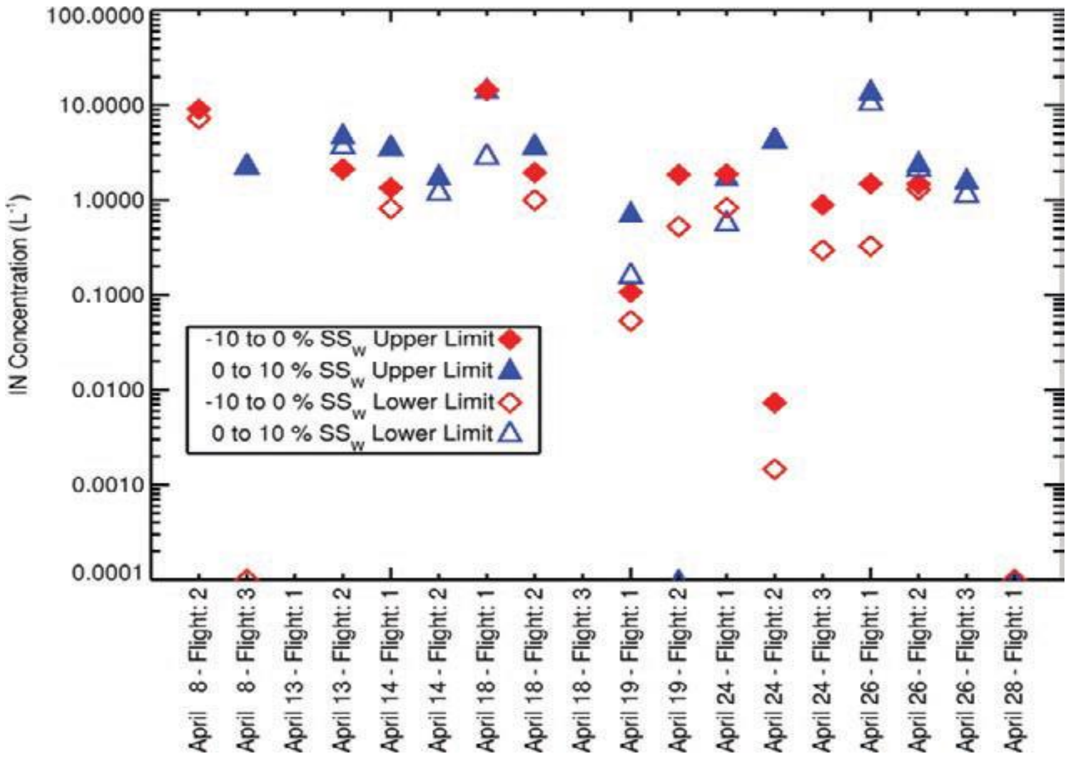
--- Autumn time (September-October 2004)
--- Sea ice + open ocean
--- Cold air outbreak;
Stronger surface fluxes as moving to southwest.
--- Driven by both cloud-top longwave cooling and surface fluxes





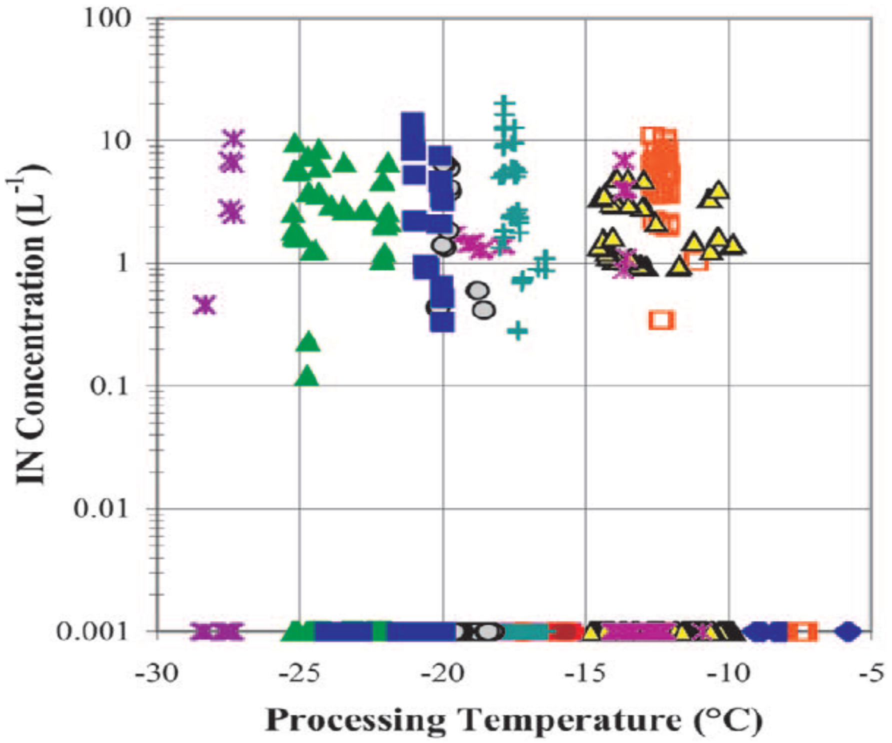
The Two Cases

ISDAC case measurements:



McFarquhar et al. 2011

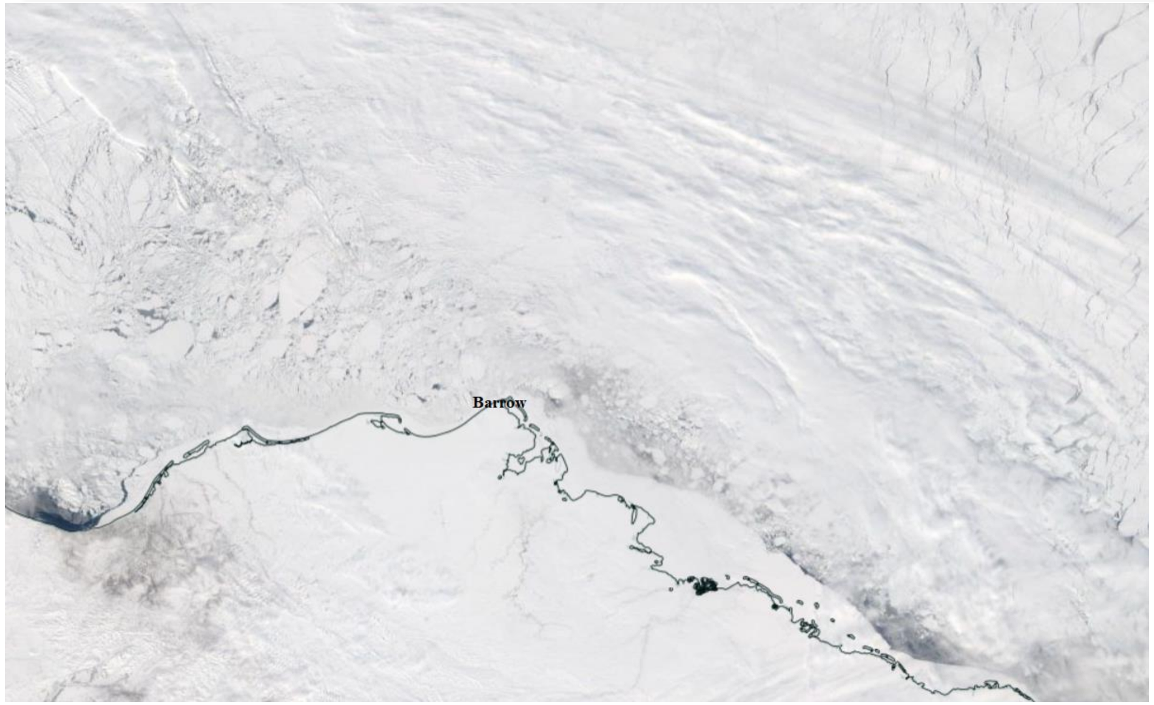
M-PACE case measurements:



Verlinde et al. , 2007

Some of the observed ice particles are broken.

ISDAC Case: Model Setup



How sensitive is the cloud to IN number concentration and IN efficiency?

Under what IN conditions does the cloud glaciate, or remain liquid, or remain mixed-phase?

For a mixed-phase cloud, how does the LWC and IWC compare?

--- Large Eddy Simulation

--- Bin microphysics scheme:
25 bins for droplets + 25 bins for ice.
--- immersion freezing
--- no riming, no ice-ice collection
(observed ice shape is pristine dendrite.)
--- no secondary ice production

--- IN number concentration:
1, 10, 100 g^{-1} (L^{-1}), consistent with the observation range.

--- IN contact angle:
more efficient IN: about 50°
less efficient IN: about 60°

--- Other setup of the model is the same as in the intercomparison study of this case (Ovchinnikov et al. 2014)

ISDAC Case: Results

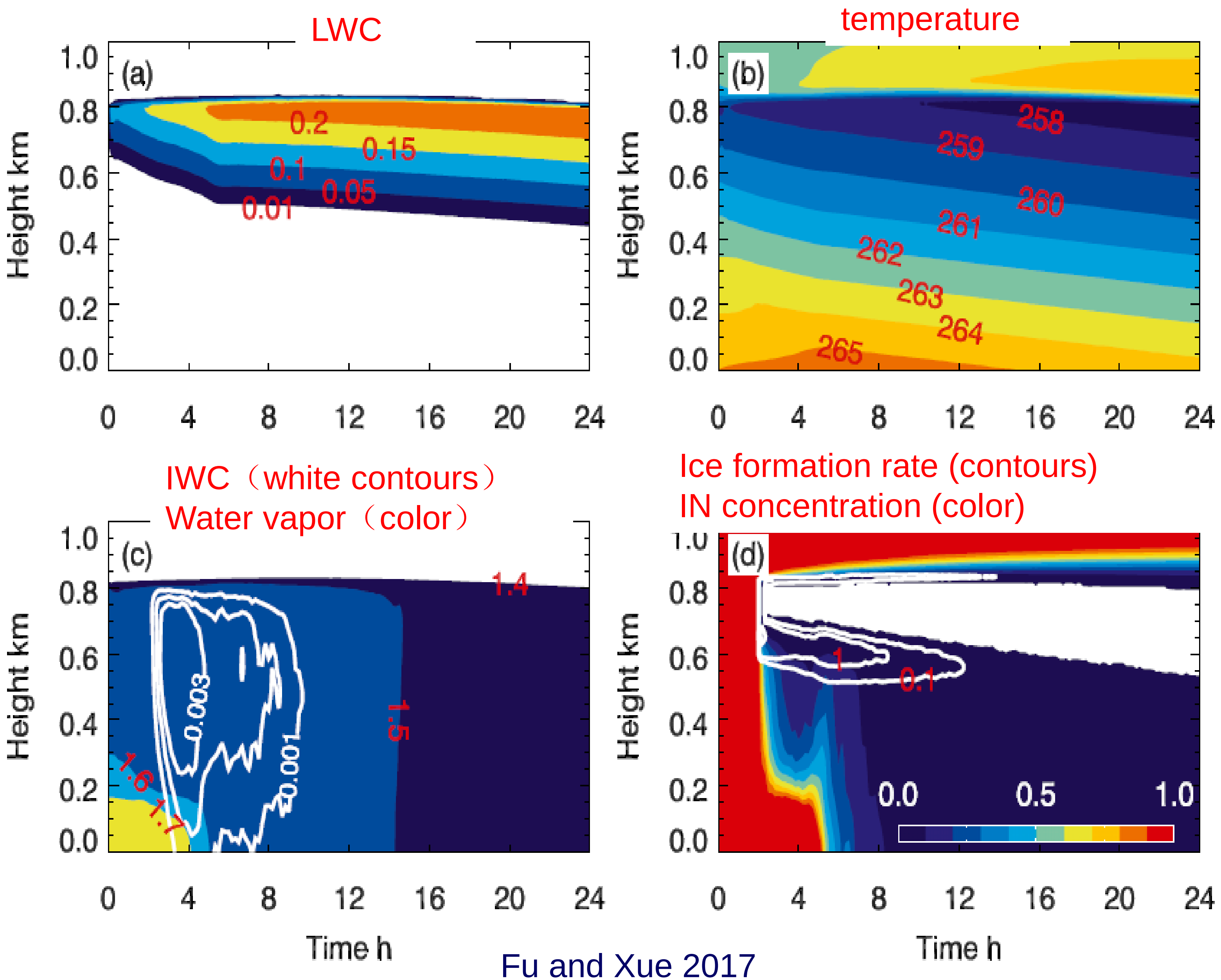
IN concentration: 1 g^{-1} (~ 1 L^{-1}).
IN efficiency: high (contact angle ~ 50°),

Feedbacks during cloud evolution:

--- longwave cooling by liquid water leads to continuous temperature decrease.

--- 3 h -12h,
Ice particles form.
IWC is not high enough to affect liquid phase.

--- after 12 h,
No new ice particles form because IN are depleted.
IWC is very low.
Cloud is liquid phase.



Fu and Xue 2017

ISDAC Case: Results

IN efficiency: high (contact angle ~50°)

--- Low IN concentration leads to low IWC. Cloud remains liquid.

--- Increasing IN concentration can increase ice formation and IWC. Cloud is mixed-phase.

--- High IN concentration leads to high IWC and glaciation. Cloud dissipated.

IN efficiency: low (contact angle ~60°)

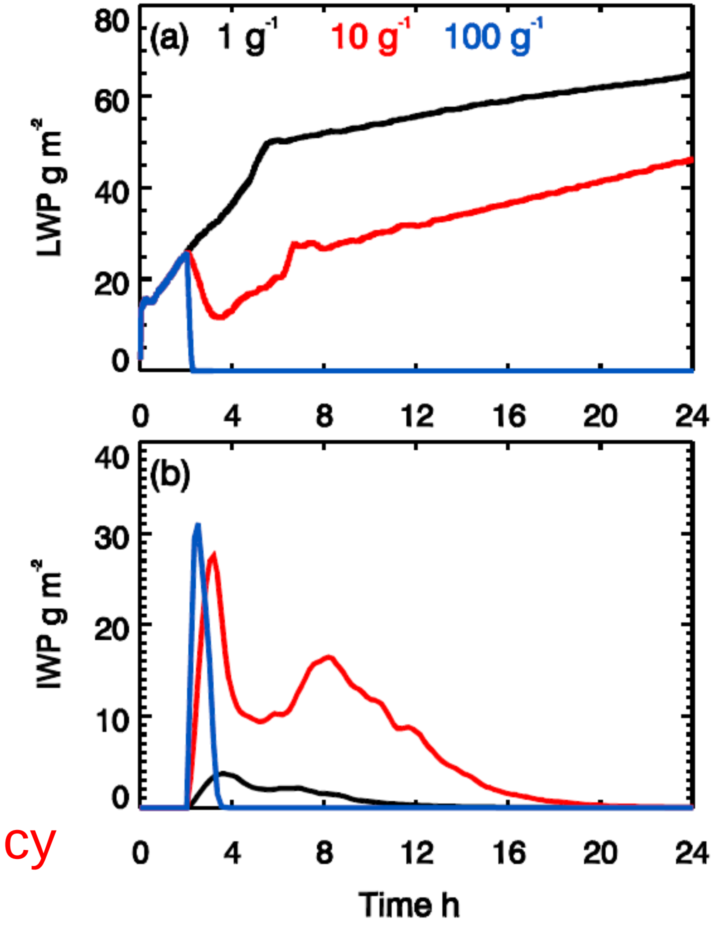
--- Slower rate of ice formation.

--- Slower conversion from liquid to ice.

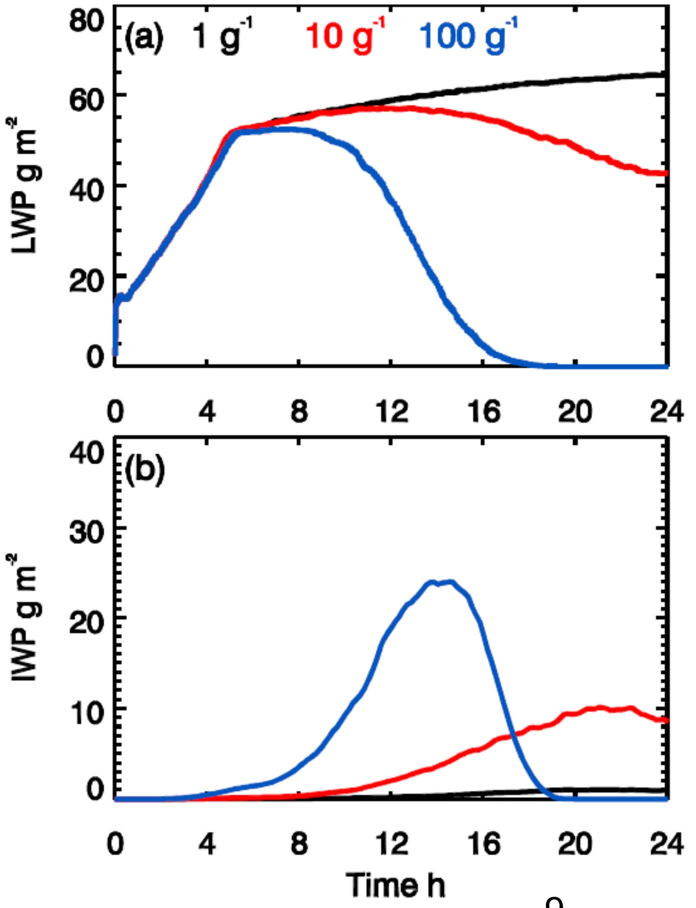
--- Cloud remains mixed-phase for a longer time.

Both IN number concentration and efficiency are crucial for maintaining mixed-phase.

IN efficiency: high
(contact angle ~50°)



IN efficiency: low
(contact angle ~60°)



Fu and Xue 2017

ISDAC Case: Results

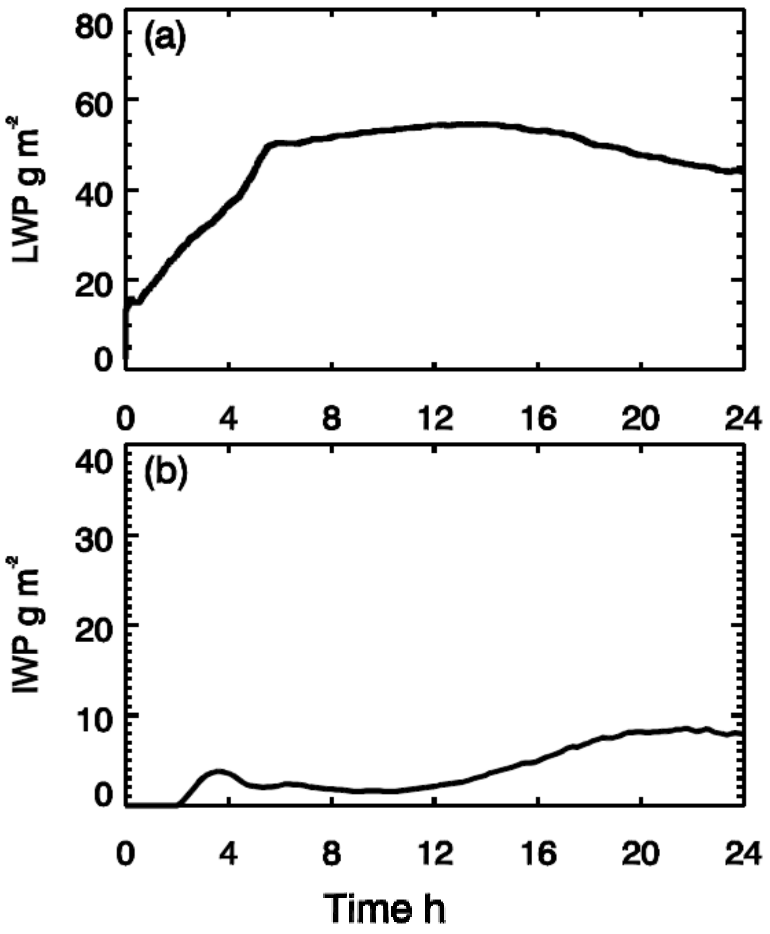
Cloud remains mixed-phase throughout the 24-hour simulation.

3-12 h， cloud temperature is relatively high, ice formation is dominated by high efficiency IN.

After 12 h， temperature decreases, ice formation is dominated by low efficiency IN, as the high efficiency IN are already depleted.

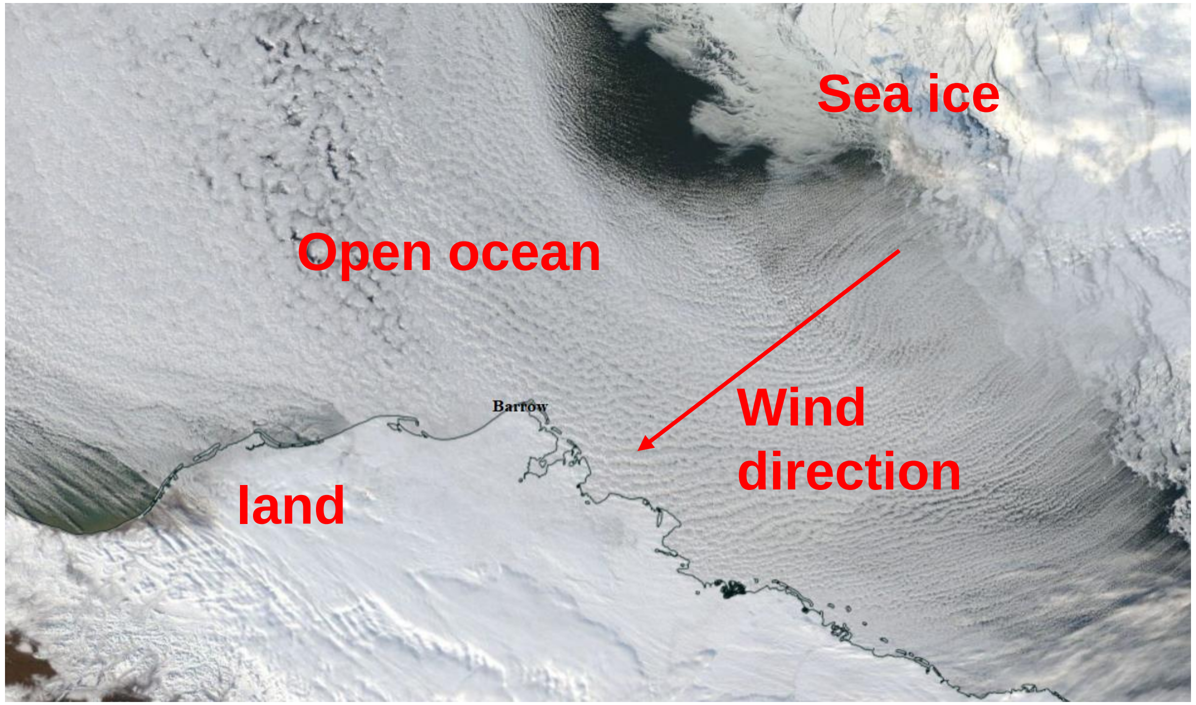
As the cloud-top temperature decreases, different types of IN (with different efficiency) are needed to keep continuous formation of ice particles, and to maintain the mixed-phase.

Cloud consists of two types of IN:
high efficiency IN： 1 g^{-1}
low efficiency IN： 10 g^{-1}



Fu and Xue 2017

M-PACE case: Model Setup



--- WRF (Weather Research and Forecasting) with 3 nested domains

--- Two moment microphysics scheme

--- immersion freezing + contact nucleation

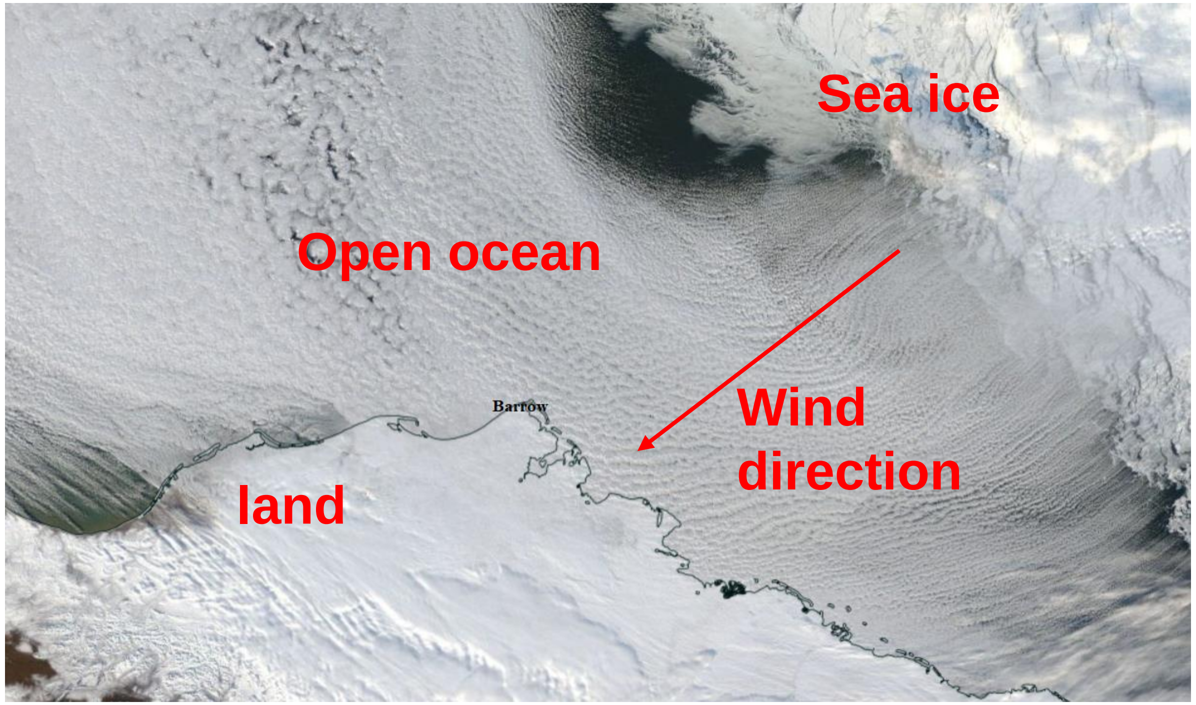
--- Secondary ice production: droplet freezing shattering; no rime splintering process. (cloud base T ~ -10°C)

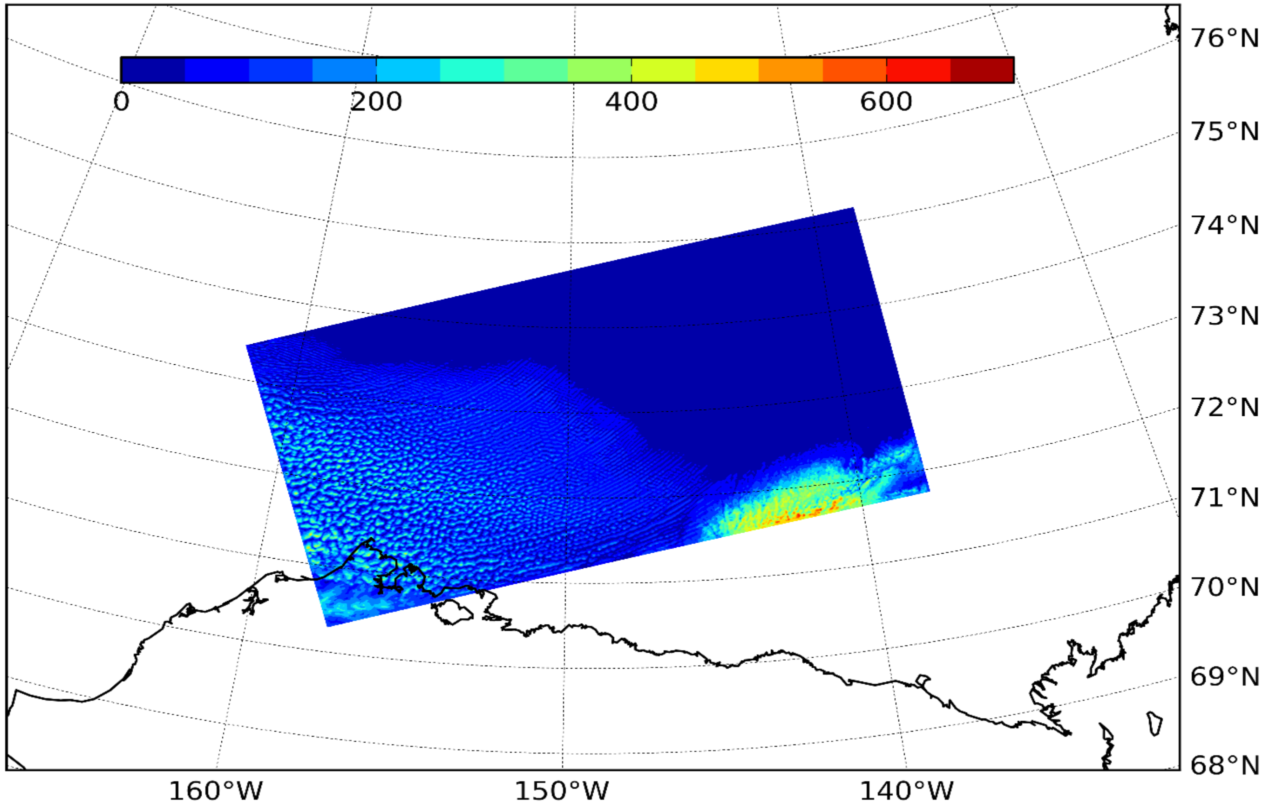
--- Including recycling of IN after ice evaporation

--- Underlying surface provides inhomogenenous surface fluxes.

Under what conditions the cloud remain mixed-phase？
What is the continuous source for ice production?
Is secondary ice production important in this case?

M-PACE case: Results





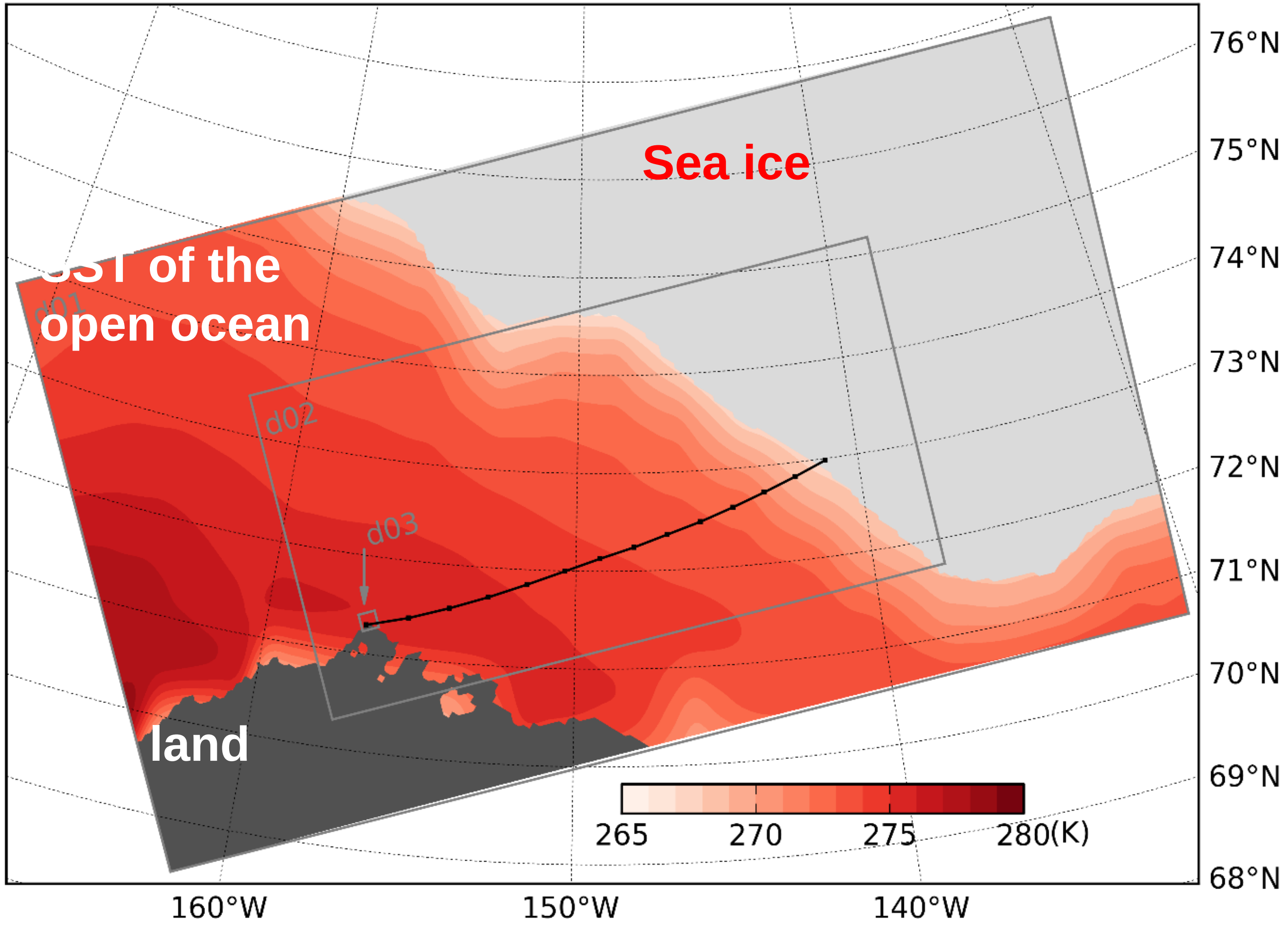
WRF simulated LWP

M-PACE case: Results

From northeast to southwest, SST increases and the sea surface fluxes gradually increase.

So the rapid rising of the cloud top was driven by both the cloud-top cooling and the strong surface fluxes.

Black line: backward trajectory



Fu et al. 2019

M-PACE case: Results

Along the backward trajectory in the last slide

Using observed IN concentration,

--- Cannot reproduce the observed IWC.

--- IN are depleted.

--- Rapid rising of cloud top leads to entrainment of IN into cloud, but still not enough.

Using observed IN concentration × 100

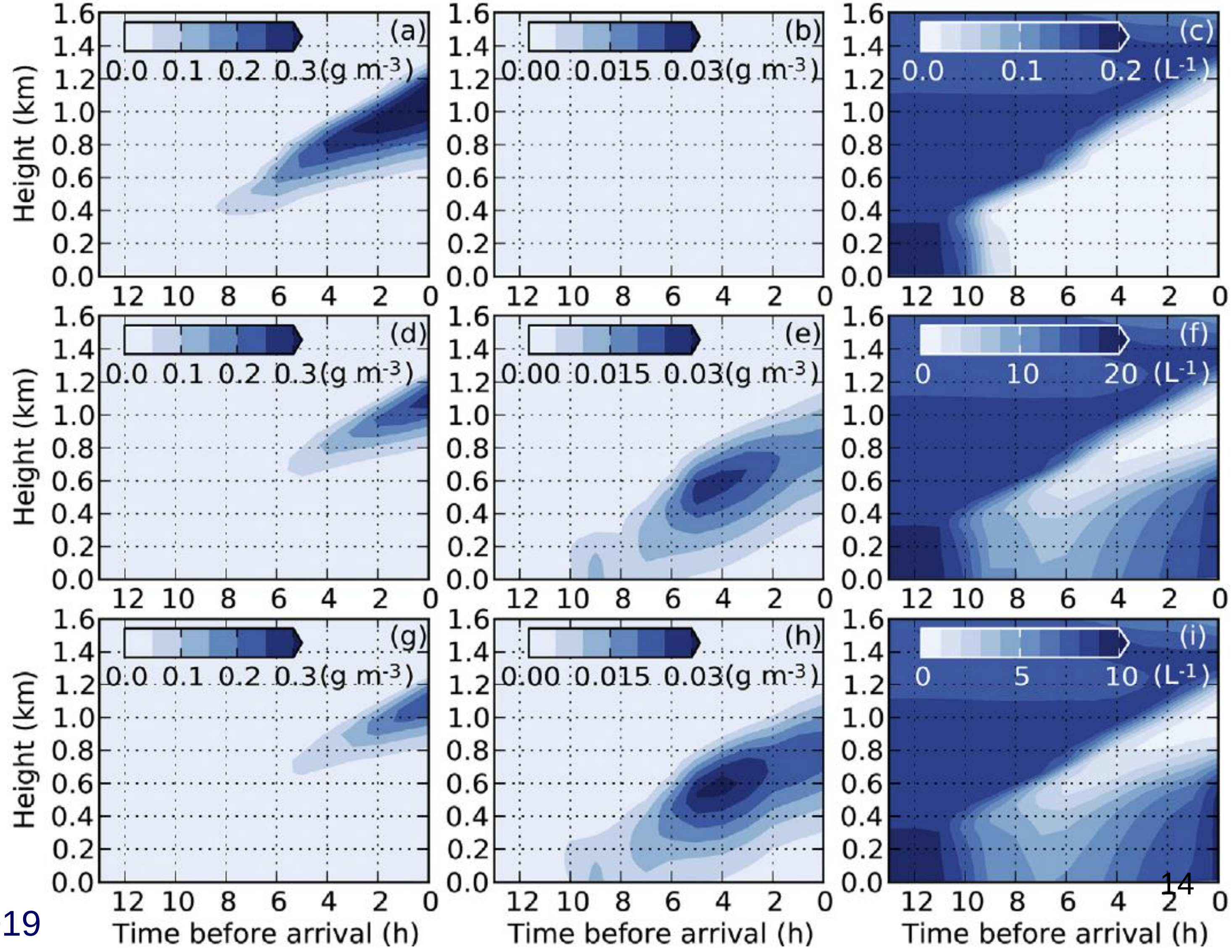
--- Can produce reasonable amount of IWC.

--- Can see cloud top entrainment of IN and recycling of IN below cloud.

Using observed IN concentration × 50,
+ droplet freezing shattering,

Drop shattering leads to more ice.

LWC　　IWC　　IN number concentration



Fu et al. 2019

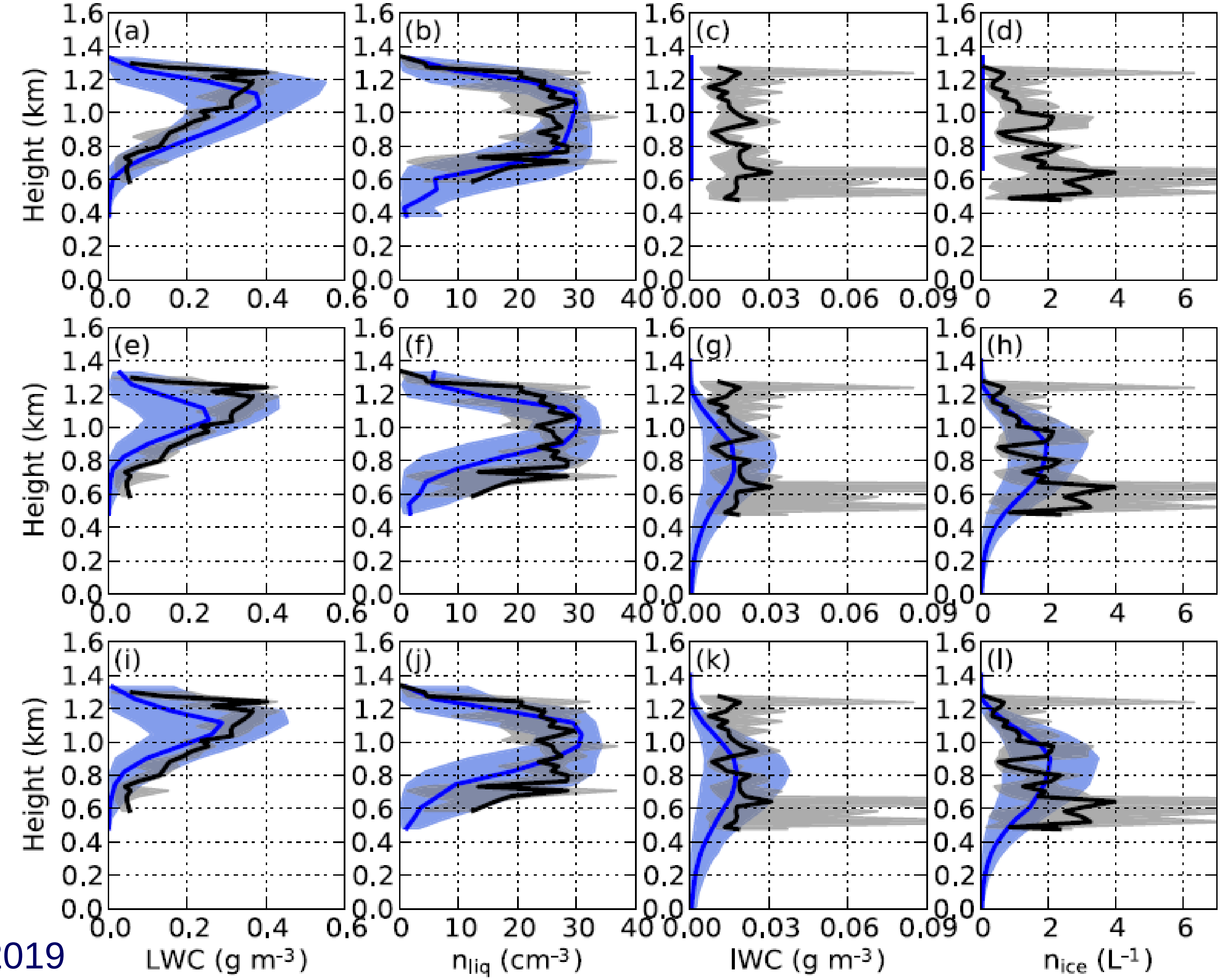
M-PACE case: Results

Black line: observation
Blue line: WRF simulaiton

Using observed IN concentration,
Simulated liquid phase is consistent with observation, but ice phase is too little.

Using observed IN concentration × 100
Simulated liquid phase and ice phase are consistent with observation.

Using observed IN concentration × 50,
+ droplet freezing shattering,
Simulated liquid phase and ice phase are consistent with observation.



Fu et al. 2019

Conclusion

ISDAC case

--- The mixed-phase cloud is very sensitive to IN number concentration and IN efficiency.

--- High efficiency IN can rapidly form ice in a relatively warm cloud.
With low IN number concentration, cloud remains liquid.
With high IN number concentration, cloud is glaciated, and then dissipated.

--- Low efficiency IN form ice at lower temperature. Ice formation is slower and the conversion from liquid to ice is slower.

--- When the cloud consists of two types of IN, the cloud would remain mixed-phase for the whole time period.

M-PACE case

--- Several ways of continuous ice production:

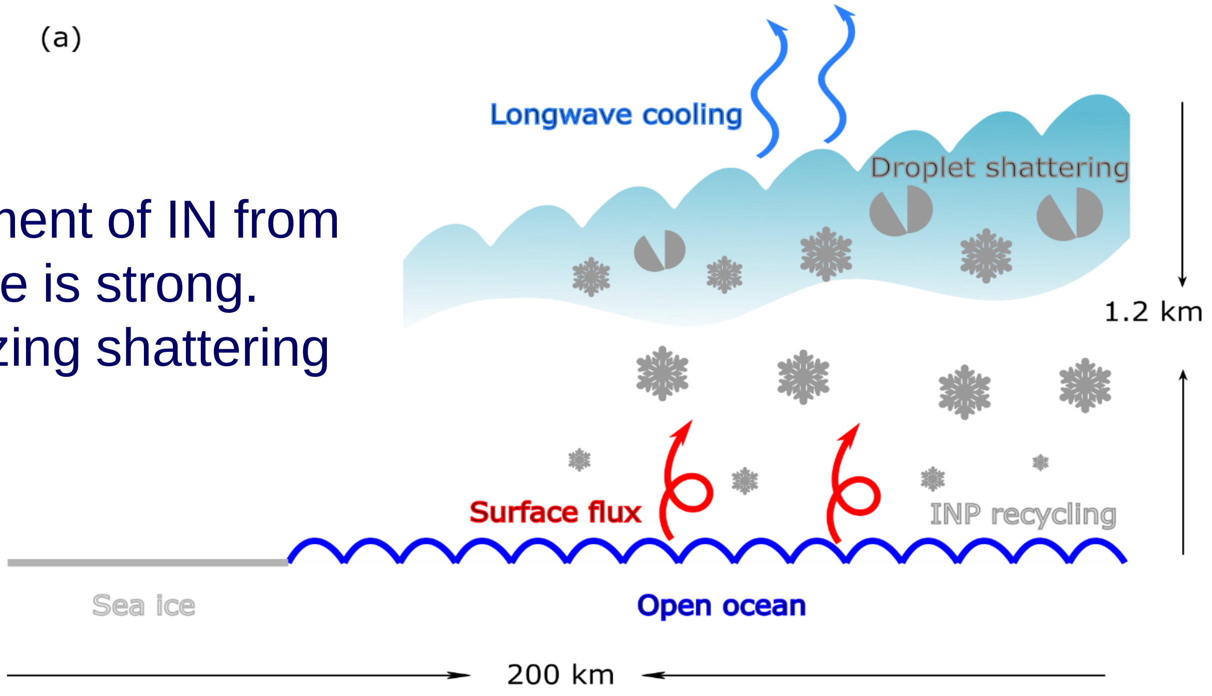
--- High surface fluxes lead to rapid rising of cloud top, and therefore more IN aerosols are entrained into the cloud.

--- IN is recycled after ice evaporation and get into the cloud to provide more IN.

--- Droplet freezing shattering is also an important way.

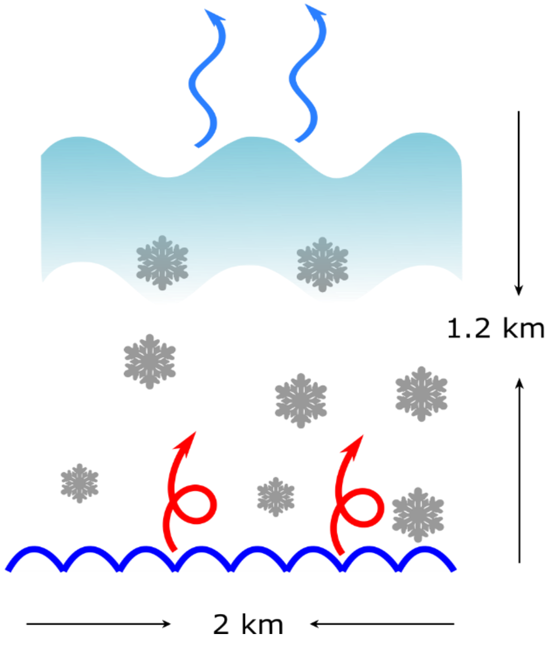
(a)

This study:
--- The entrainment of IN from free troposphere is strong.
--- Droplet freezing shattering is important.



(b)

Previous studies



Fu 2021, PhD thesis

Thank You!