Seasonal variations of Arctic low-level clouds and its linkage to sea ice seasonal variations

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Overview

1. Motivation
2. Data and method
   - Data Information
   - Surface Type Stratification
   - Sea Ice Melt and Freeze Onset Dates
3. Results
   - Seasonal variations of low-level cloud liquid water path (LWP) over different surface types
   - Physical processes linking sea ice to the seasonal variations of LWP
4. Summary

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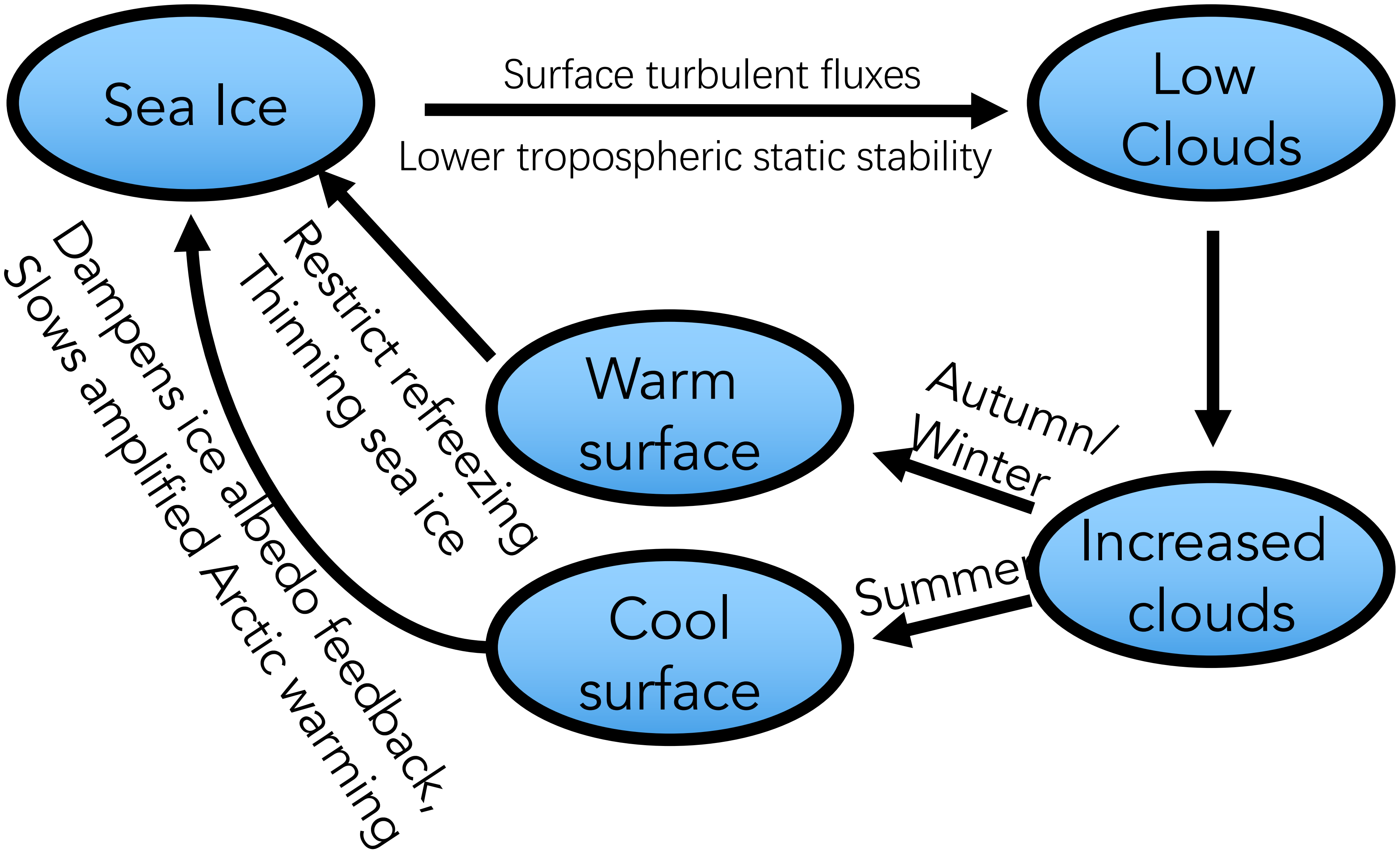
Motivation

Among the dynamic and thermodynamic processes related to the Arctic sea ice variability, cloud-sea ice interactions are one of the most poorly understood aspects and the recent focus!



Motivation

- Many of the previous Arctic sea ice-cloud interaction studies focused on **interannual or longer time scales**.
- It remains an open question:

To what extent the coupling mechanisms of Arctic sea ice and low-level clouds at interannual scales are relevant at the seasonal scale?

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Data and Method

Footprint-level data

- Source:
  - Ed RalB1 CALIPSO-CloudSat-Clouds and the Earth's Radiant Energy System (CERES)-Moderate Resolution Imaging Spectrometer (MODIS) (C3M) dataset (Kato et al., 2010).
- Variables used in this study:
  - Sea ice concentration (SIC), vertical profiles of temperature, water vapor, and cloud properties
- Time period:
  - July 2006-June 2010

Regrided data

- To increase the temporal resolution, we grid the footprint-level data (up to 2759 footprints in the latitude band of 70°N–82°N) by averaging all available data within a grid box.
- Our results are obtained at the resolution of **2° in longitude by 0.5° in latitude** (~50×50 km).
- This ensures the data at the majority of grid points (65%) has a temporal resolution shorter than 3 days and **95% of grid points have a temporal resolution shorter than a week**.

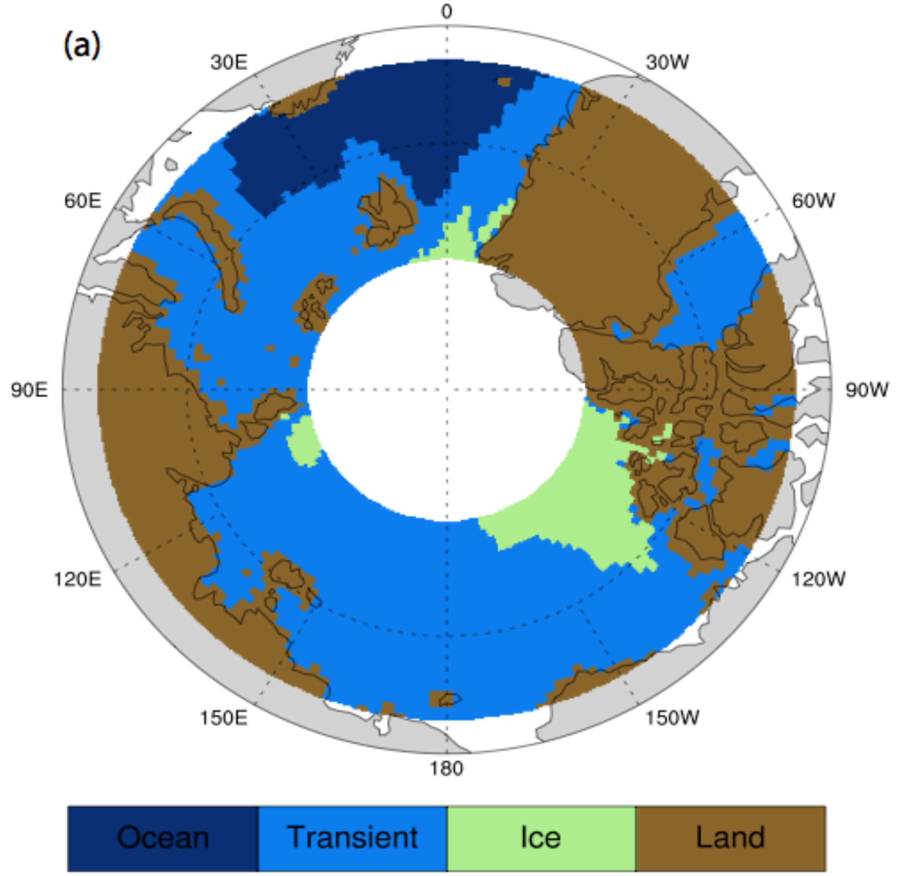
ERA-Interim data

surface evaporation flux

Data and Method

-Surface type stratification

Maps of surface type



(i) A grid is called *Land* if the sum of area percentage of ocean and sea ice in that grid is less than 99% over more than 50% of the time

For the grid points not belonging to *Land* type,

(ii) *Permanent Ocean* type is a grid where SIC < 15% over 99% of the time;

(iii) *Permanent Ice* type is a grid where the SIC exceeds 15% over 99% of the time;

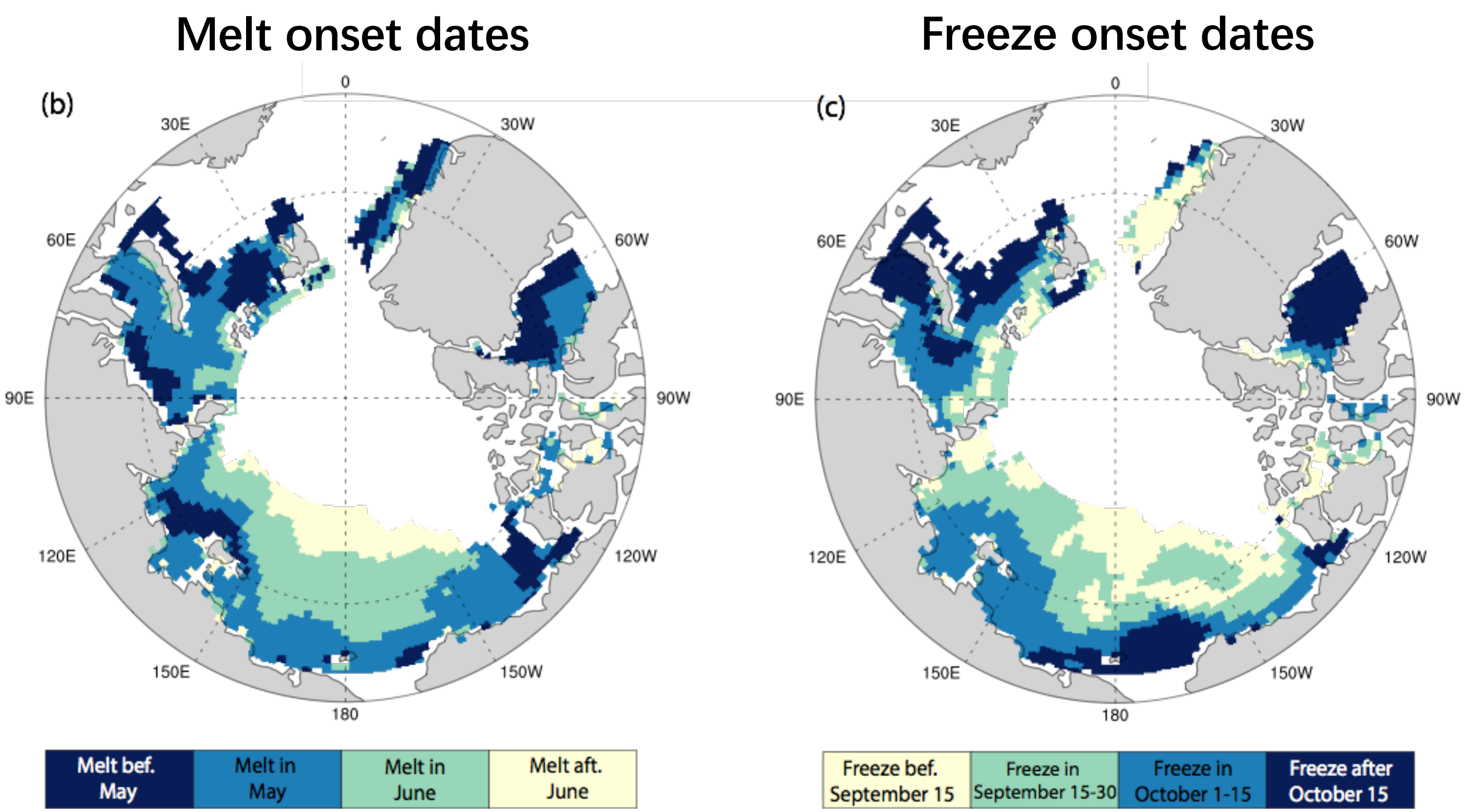
(iv) the remaining grids are placed into the *Transient Ice* type.

Data and Method

-Sea ice melt and freeze onset dates

The **onset date of sea ice melt** at a grid point is defined as the day after which its SIC shows a negative daily tendency for more than 80% of the time with a total decrease of SIC exceeding 15% within a one-month period.

The **onset date of sea ice freeze** is defined as the day after which SIC shows an increasing daily tendency for more than 80% of the time with the total increase of SIC exceeding 15% within a one-month period.



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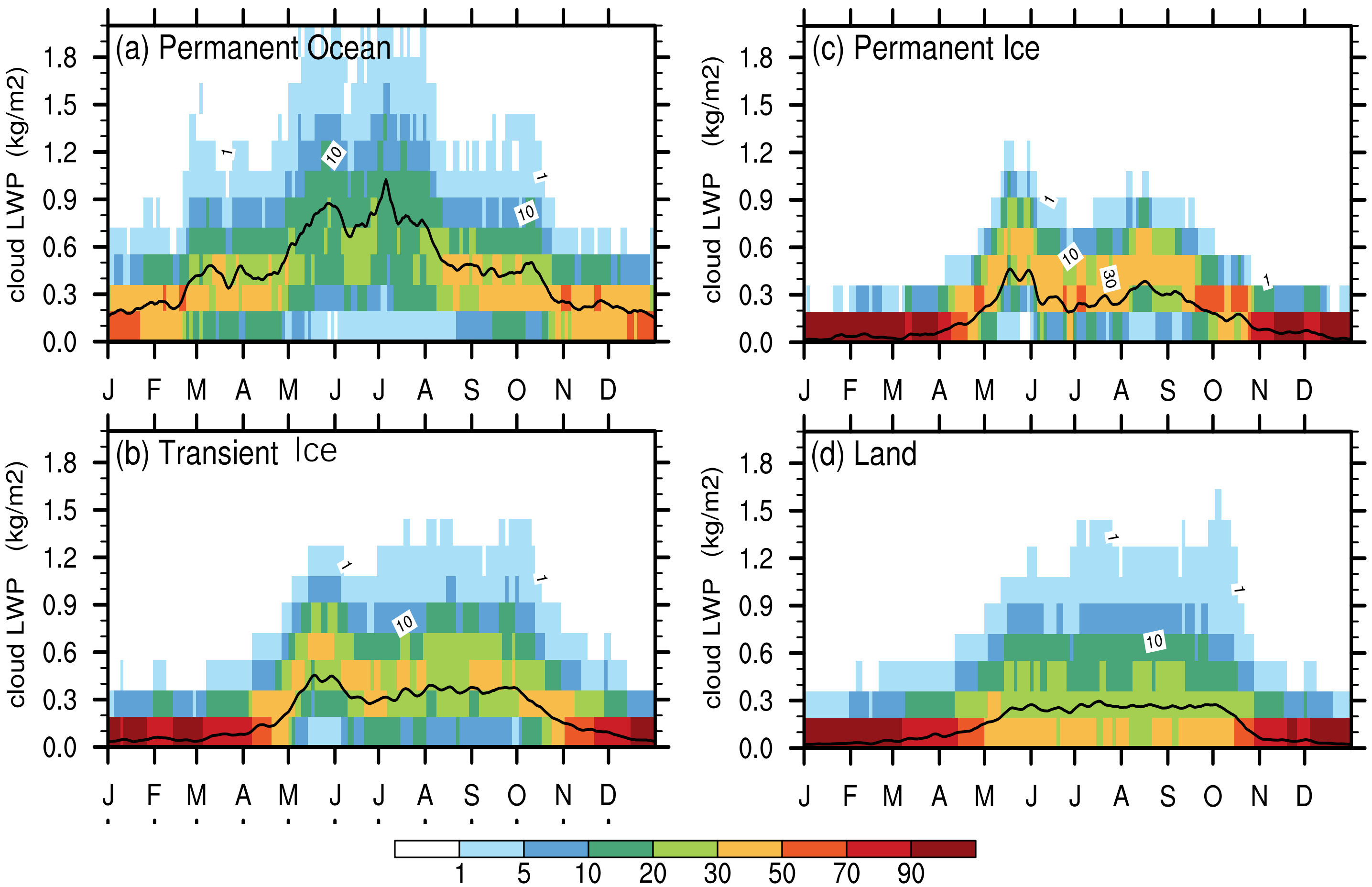
Seasonal variations of low-level cloud LWP over different surface types

Seasonal cycle of LWP (units: kg/m2) represented by the **spatial variability (PDF, shadings)** and **areal-mean value (black curve)** over four surface types



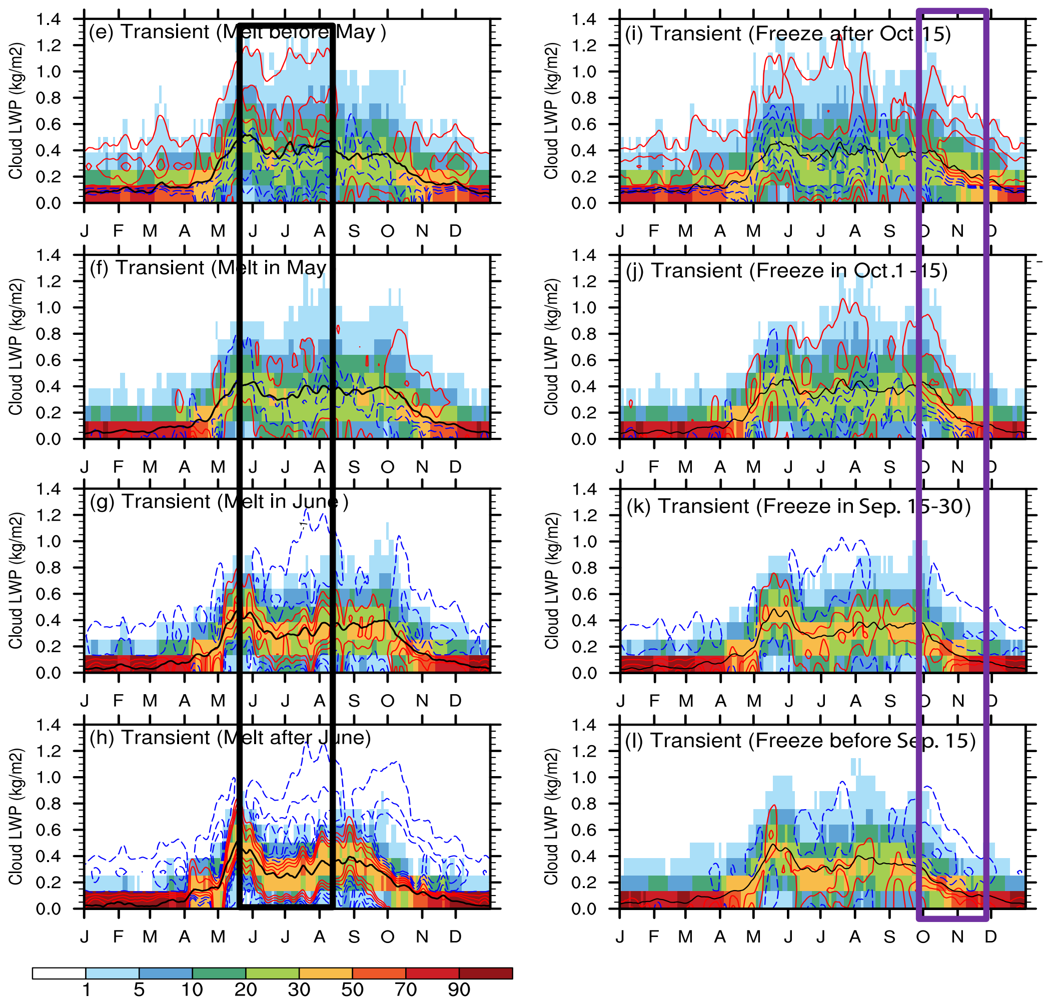
Annual mean	Surface type			
	Permanent Ocean	Transient Ice	Permanent Ice	Land
LWP (kg/m^2)	0.46	0.22	0.16	0.15

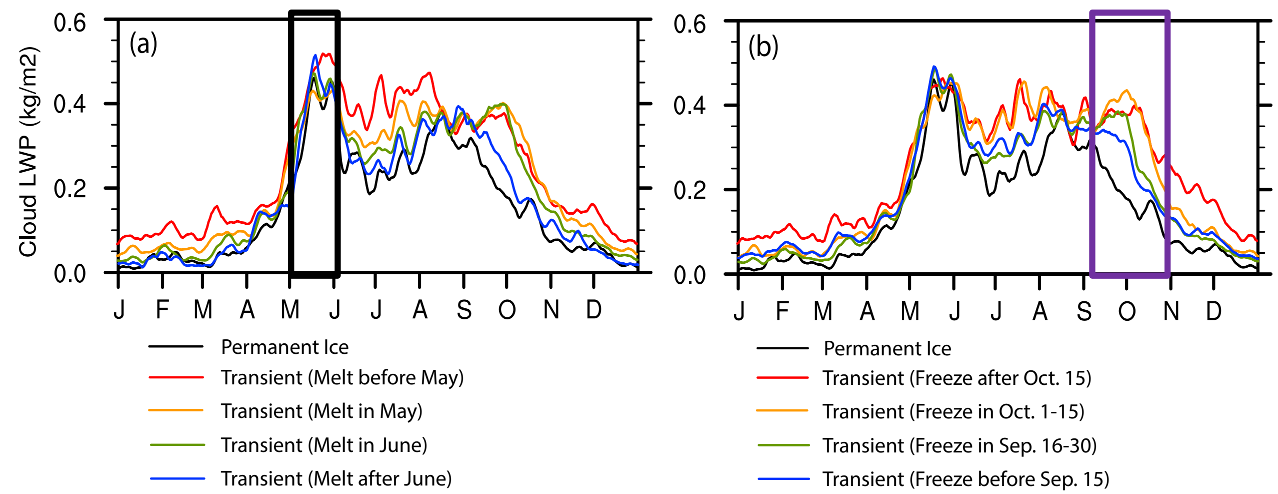
The Arctic low cloud LWP seasonal cycle exhibits a strong surface type dependence!

- Cold months: PO VS other types
- Warm months: “V” shape mid-summer evolution over PI and TI

Seasonal variations of low-level cloud LWP over TI sub-regions with different sea ice melt/freeze onset dates

Seasonal cycle of LWP over sub-regions of transient ice region. Contours indicate the difference of the PDF for each sub-region with the PDF over all grid points belonging to *Transient Ice* type.





Sea ice influence on LWP seasonality?

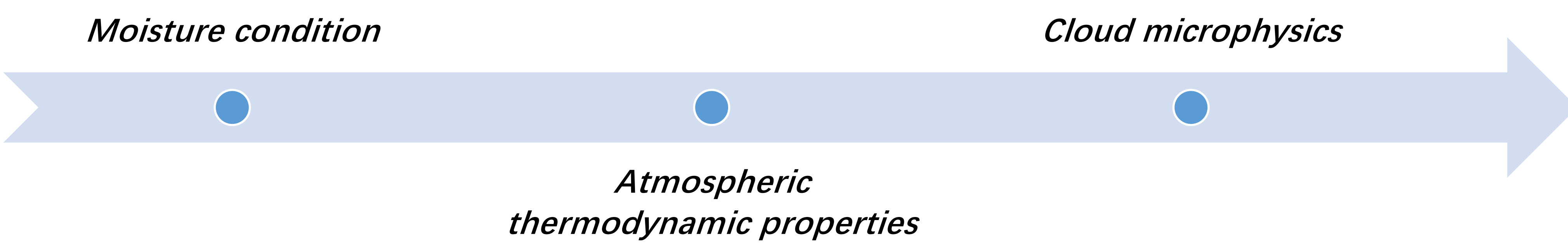
- The May LWP peak does NOT shift earlier/later over earlier/later sea ice melt regions;
- Earlier/later sea ice melt regions possess larger/smaller LWP and a broader/narrower PDF in the **mid-summer**. ☑

- The Autumn LWP decrease shifts earlier/later time over regions where sea ice freeze earlier/later. ☑
- Later/earlier sea ice freeze regions possess larger/smaller LWP and a broader/narrower PDF particularly **in Oct-Nov**. ☑

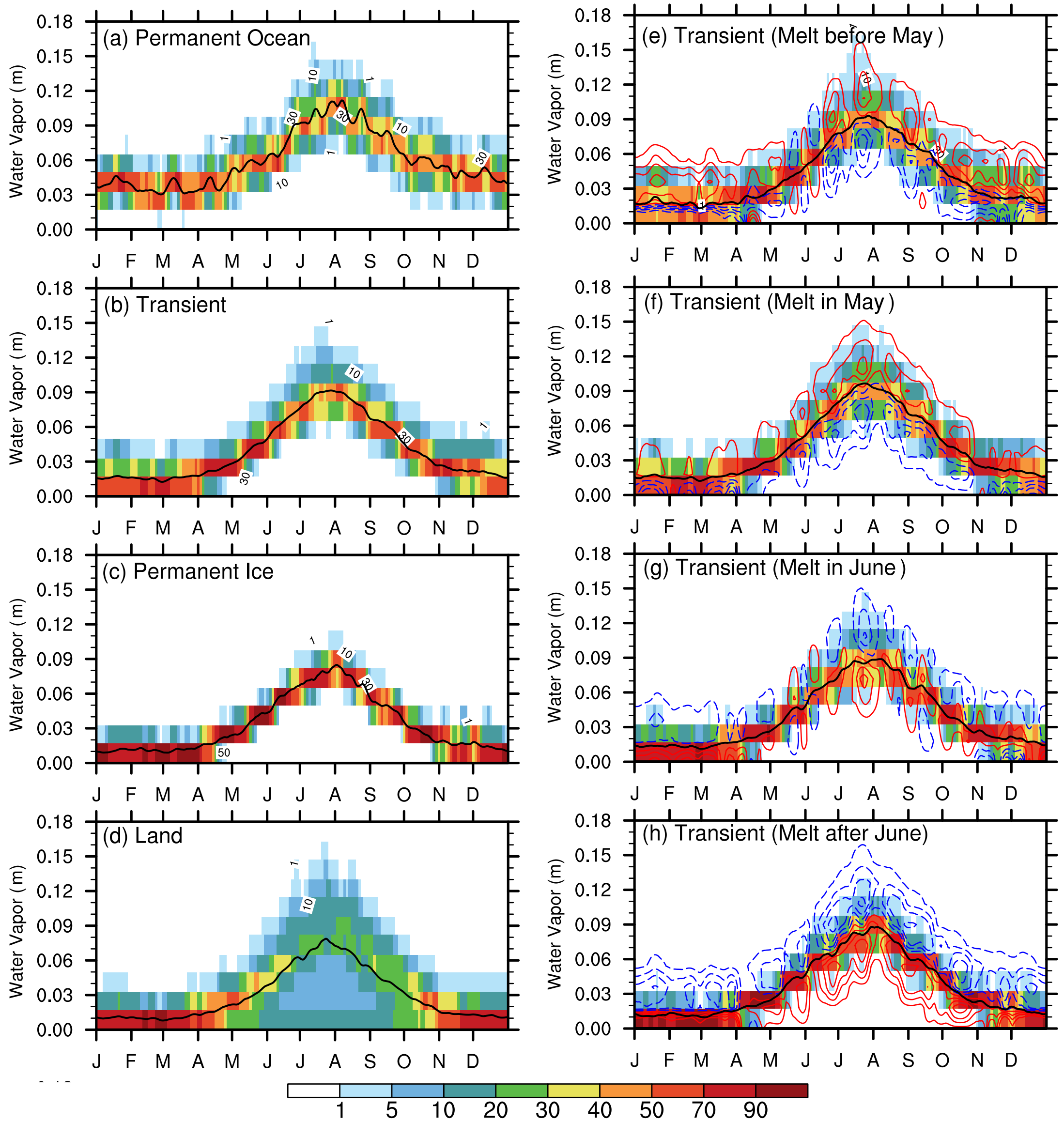
Physical processes linking sea ice to the seasonal variations of low-level cloud LWP

Questions to be answered:

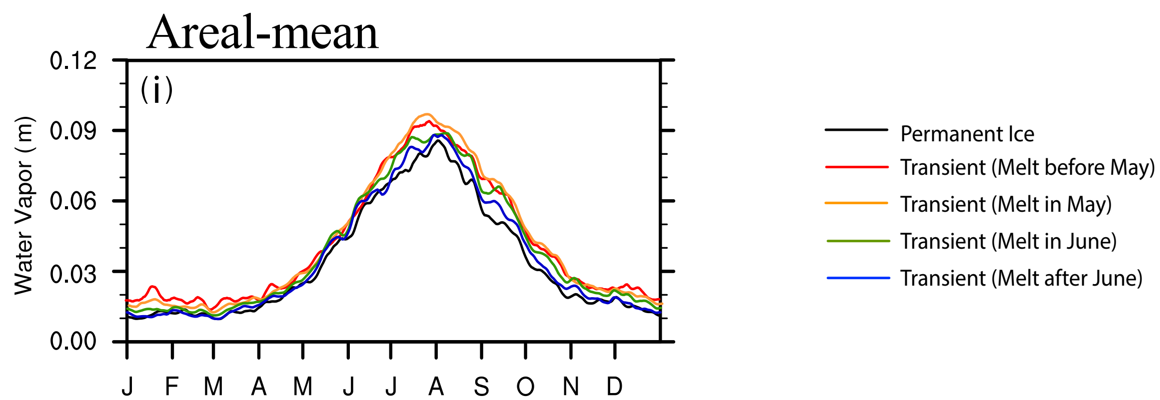
- Why is the annual mean and seasonal cycle of the low-level cloud LWP dependent on surface type?
- What factors explain the shape of the LWP seasonal cycle over *Transient Ice* and the regional differences across sea ice melt onset dates?
- What factors (besides sea ice variation) play a dominant role in the seasonal cycle of LWP?
- Are these factors modified by the nature of underlying surface?



Physical processes linking sea ice to the seasonal variations of low-level cloud LWP-Moisture condition



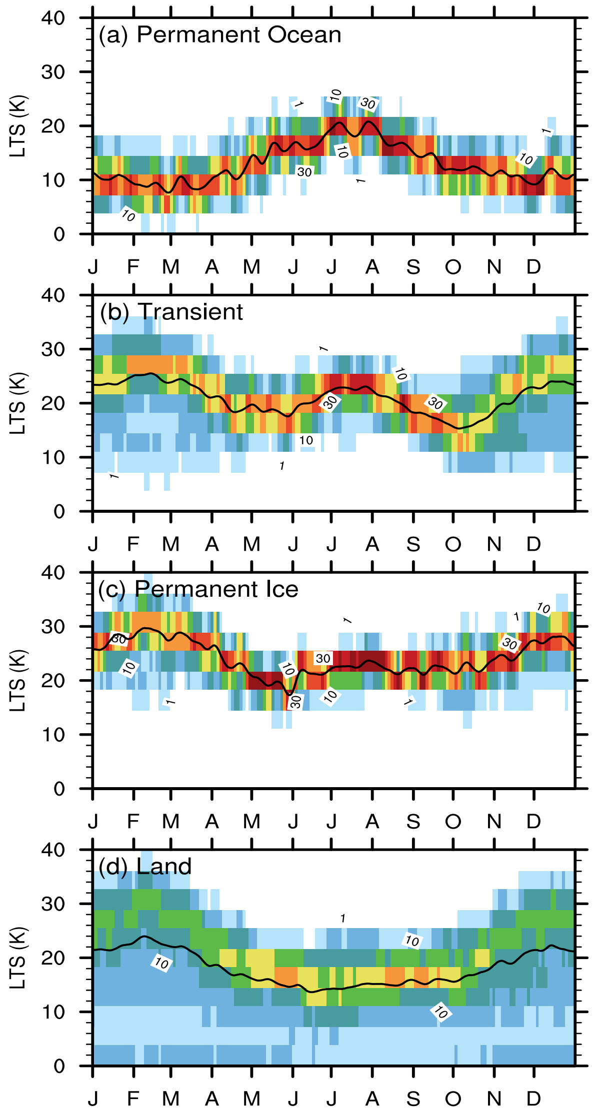
Annual mean	Surface type			
	Permanent Ocean	Transient Ice	Permanent Ice	Land
LWP (kg/m^2)	0.46	0.22	0.16	0.15
WV (cm)	5.95	3.97	3.30	2.95



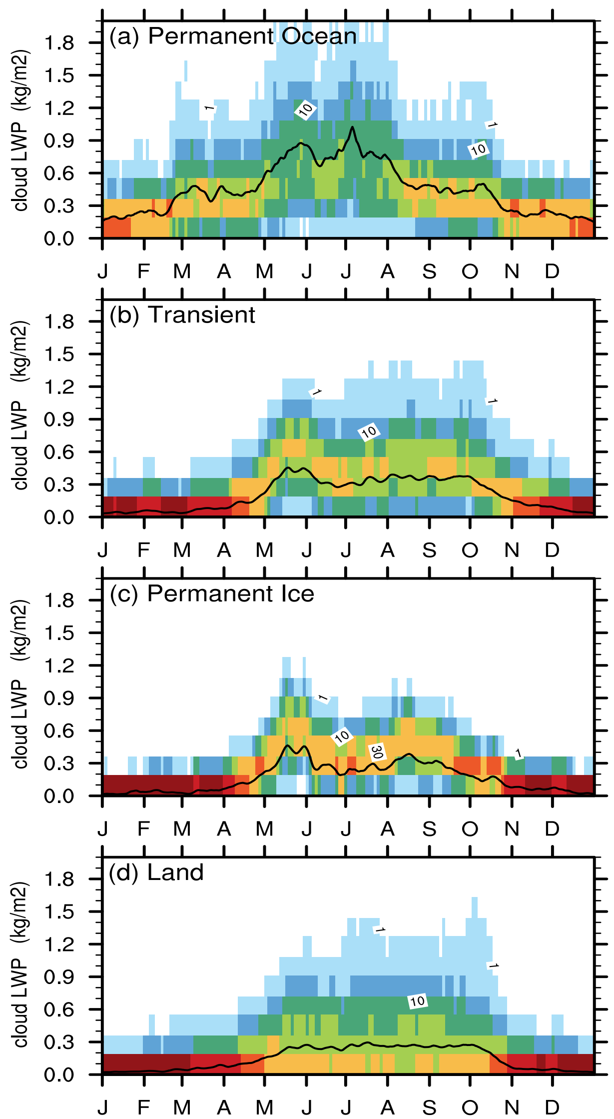
- Moisture condition at different surface types is consistent with LWP in terms of annual mean values.
- However, the evaporation changes linked to underlying surface makes minor contribution to the WV seasonal cycle, which shows little contrast by surface type → **WV cannot be a primary controlling factor to LWP evolution.**

Physical processes linking sea ice to the seasonal variations of low-level cloud LWP- Atmospheric thermodynamic properties

Lower tropospheric stability (LTS) $\theta_{700hPa} - \theta_{sfc}$



Low-level cloud LWP

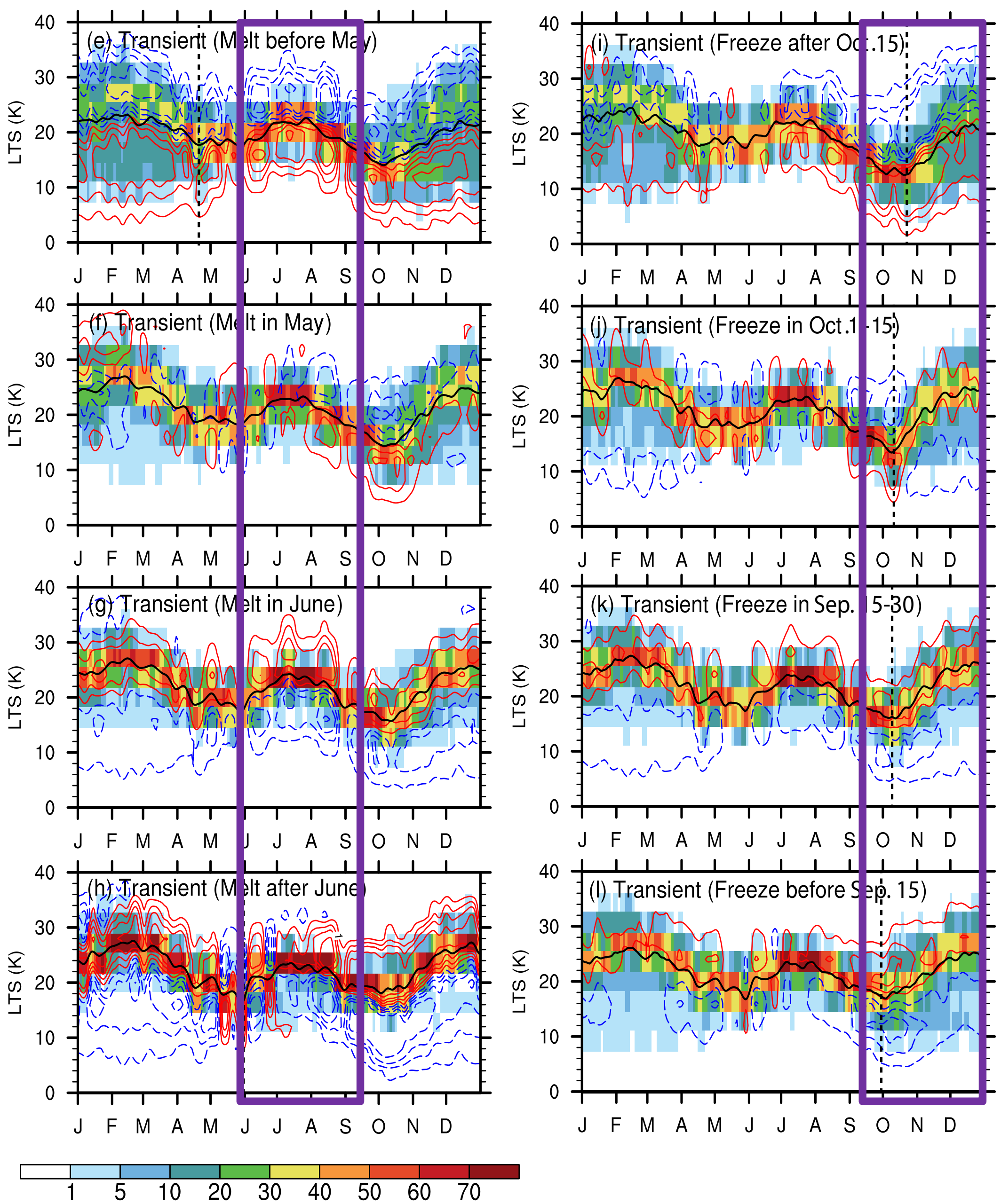


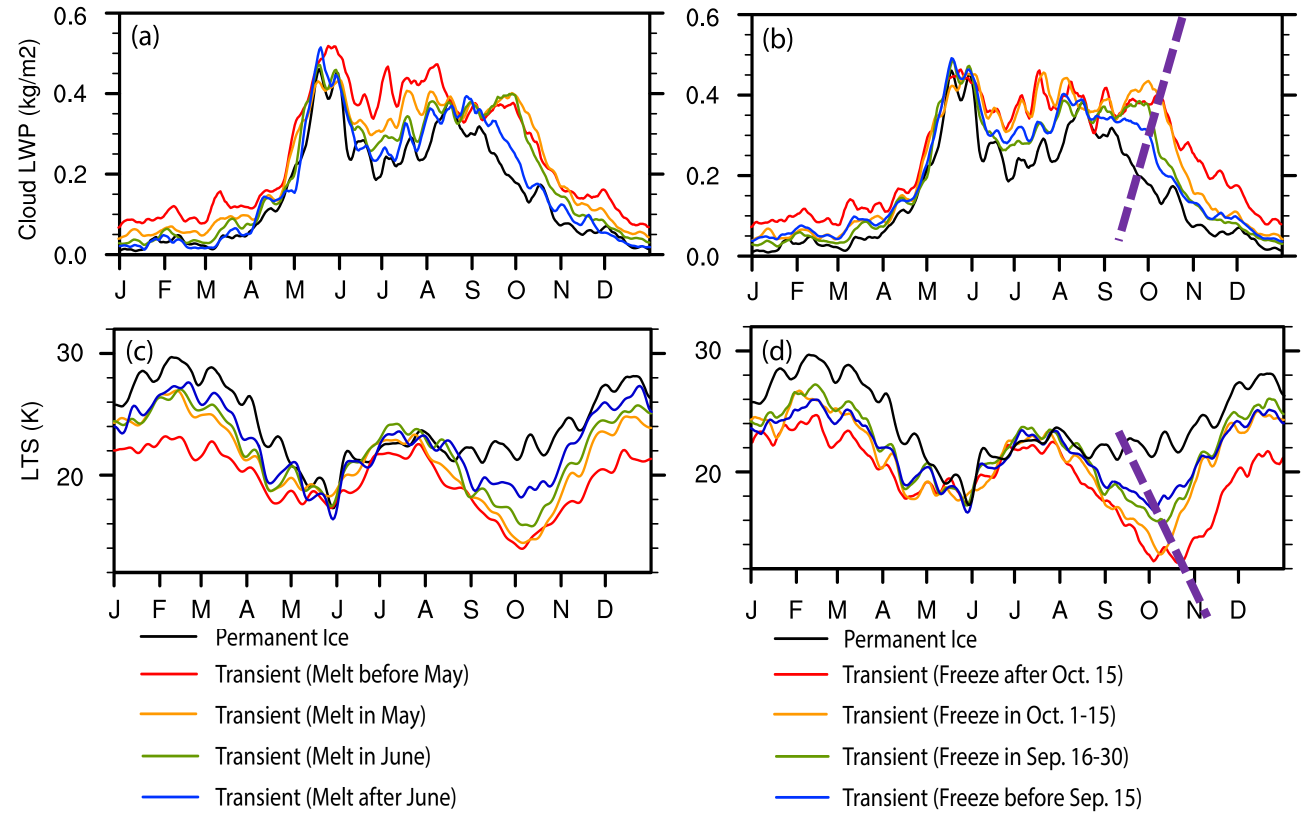
Annual mean	Surface type			
	Permanent Ocean	Transient Ice	Permanen t Ice	Land
LWP (kg/m^2)	0.46	0.22	0.16	0.15
LTS (K)	12.95	21.23	24.09	18.05

Variations in LTS corresponds well with the seasonal cycle of LWP!

- Annual mean: lower LTS ~ larger LWP
- Seasonal variation in warm months :
  - Out-of-phase variation of LWP and LTS over *Permanent Ice* and *Transient Ice* region;
  - In-phase variation of LWP and LTS in warm months over *Permanent Ocean* region (where is more unstable year round).

Physical processes linking sea ice to the seasonal variations of low-level cloud LWP- Atmospheric thermodynamic properties

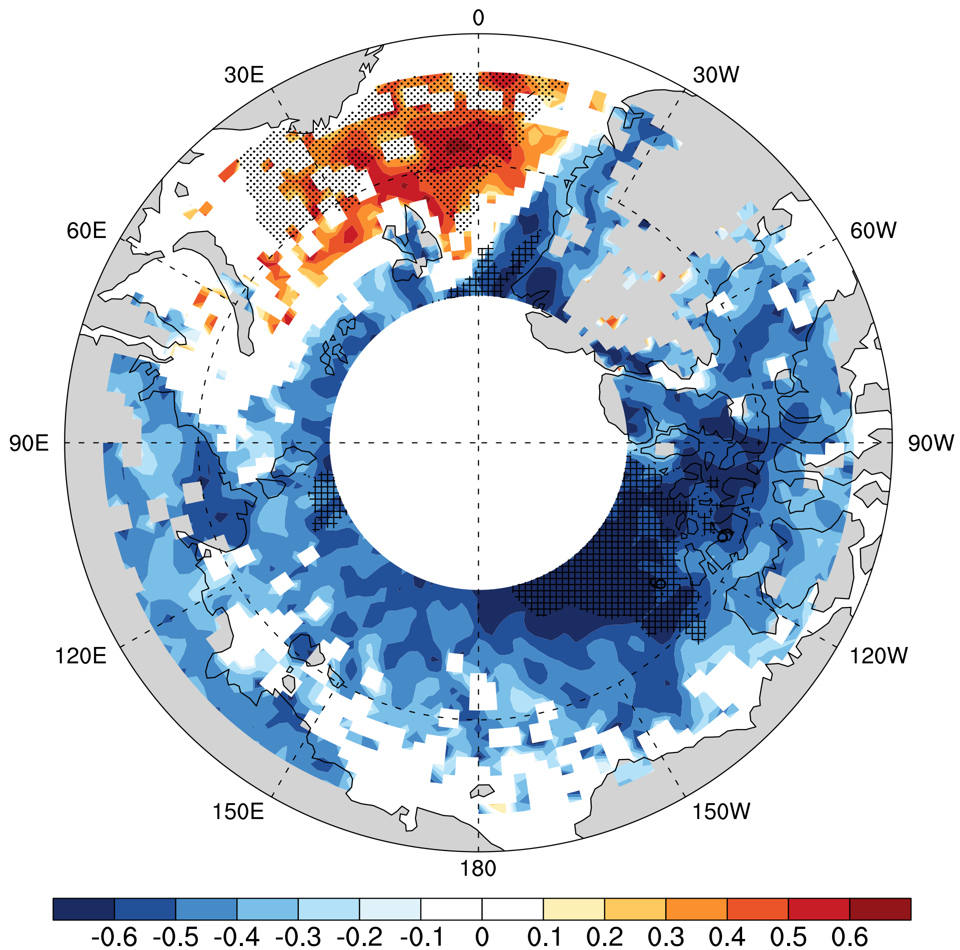




Variations in LTS explain the warm season differences in the variation of LWP with respect to sea ice melt onset and freeze!

Physical processes linking sea ice to the seasonal variations of low-level cloud LWP- Atmospheric thermodynamic properties

Map of temporal correlations of LWP with LTS during the warm months (April-October)



Confirm the significant relation between LTS and LWP across all Arctic regions!

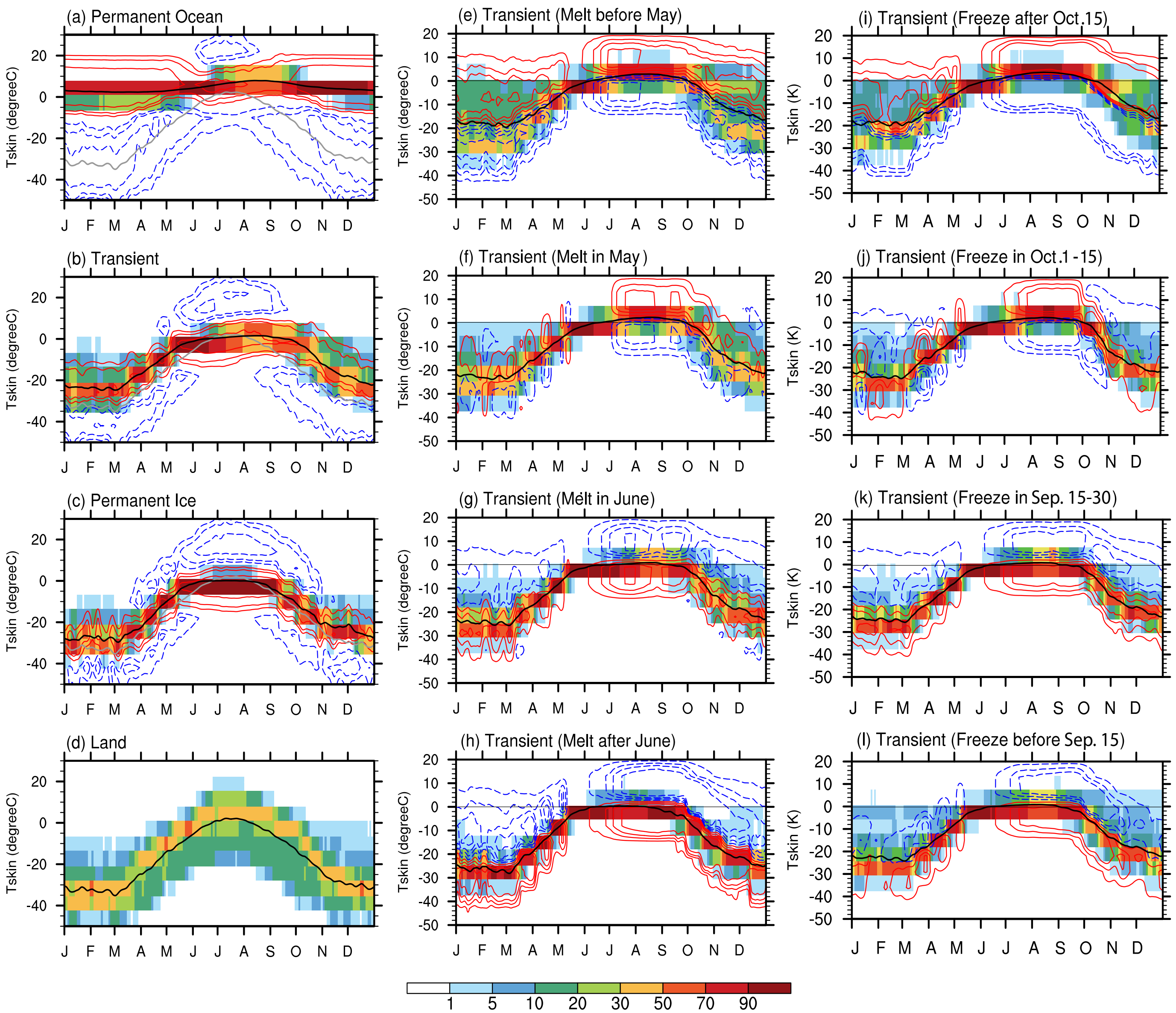
Variations in LTS is the primary factor controlling the seasonality of low-level cloud LWP and timing of the key turning points of the seasonal cycle of LWP over different surface types!

Remaining question:
How surface type and sea ice change modify the LTS?

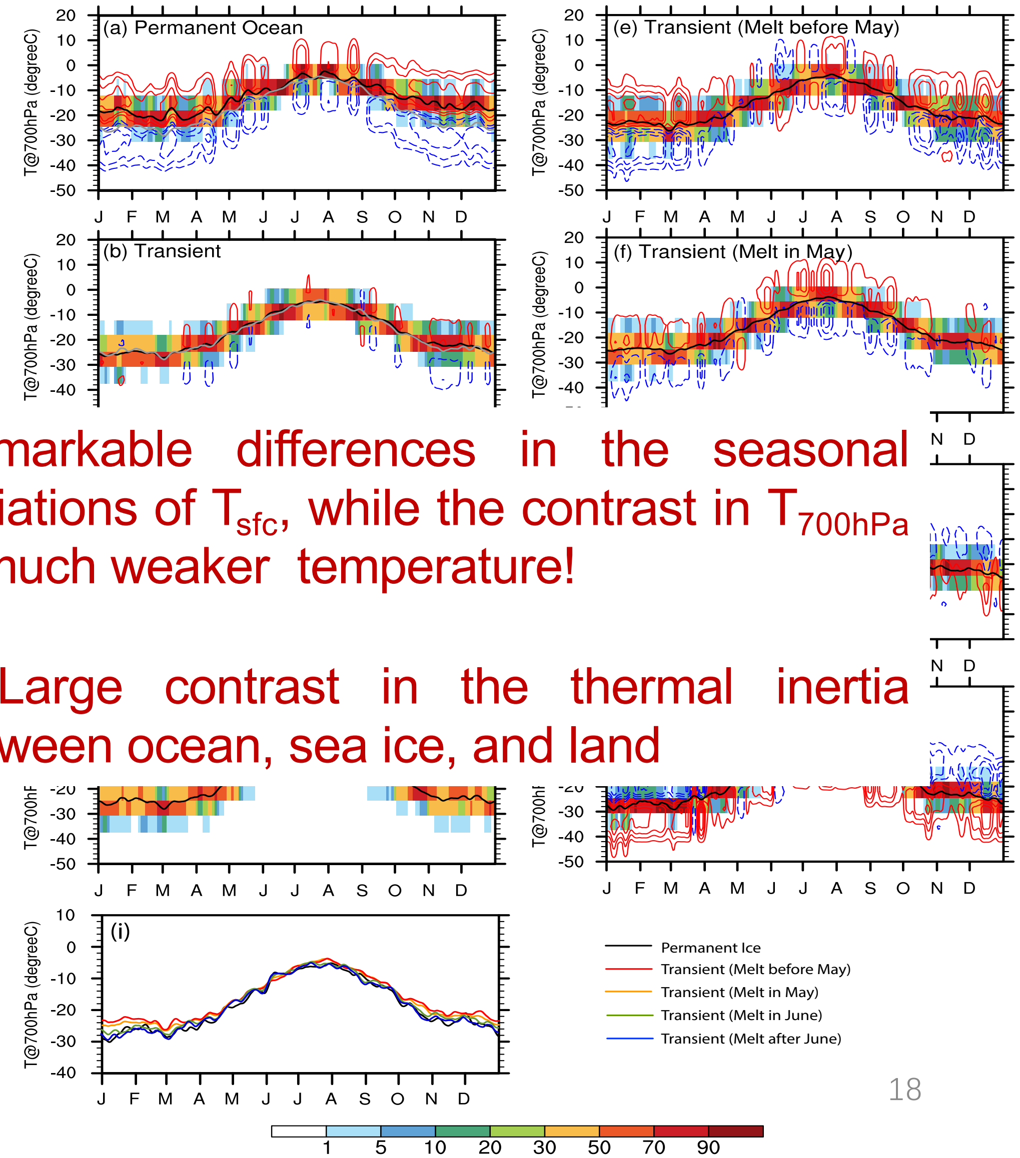
Physical processes linking sea ice to the seasonal variations of low-level cloud LWP- Atmospheric thermodynamic properties

Seasonal cycle of surface temperature

Grey curves overlaid in panels a–c is the areal-mean surface temperature over *Land* surface.



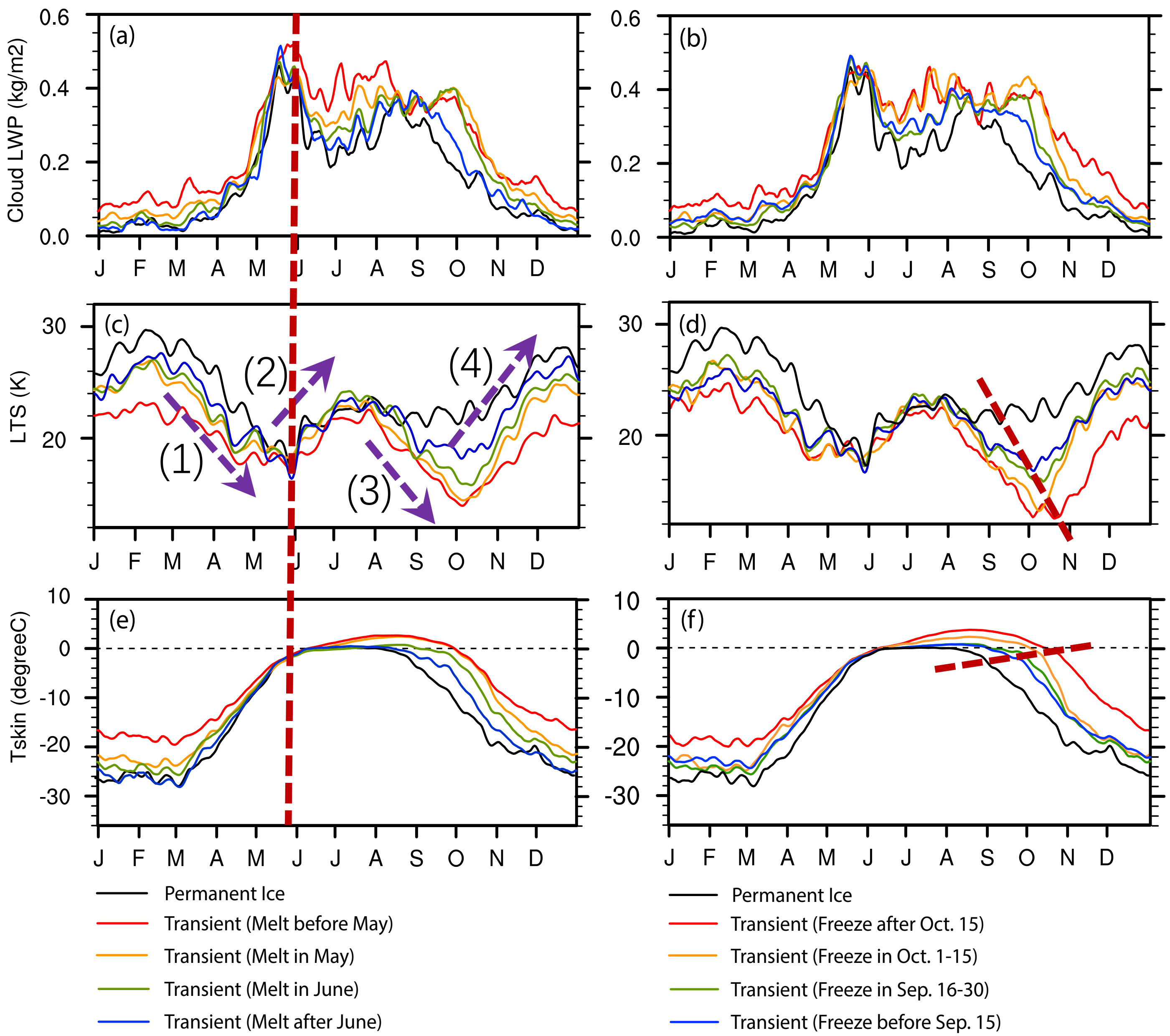
Seasonal cycle of the temperature at 700 hPa



Remarkable differences in the seasonal variations of T_{sfc}, while the contrast in T_{700hPa} is much weaker temperature!

~ Large contrast in the thermal inertia between ocean, sea ice, and land

Physical processes linking sea ice to the seasonal variations of low-level cloud LWP- Atmospheric thermodynamic properties



(1) The May LTS minimum ← rapid surface skin temperature increase in response to increased solar insolation that results from the low thermal inertia of the ice surface, outpacing the warming in the lower troposphere.

The timing of the LTS as well as T_{sfc} minimum is not sensitive to sea ice melt dates!

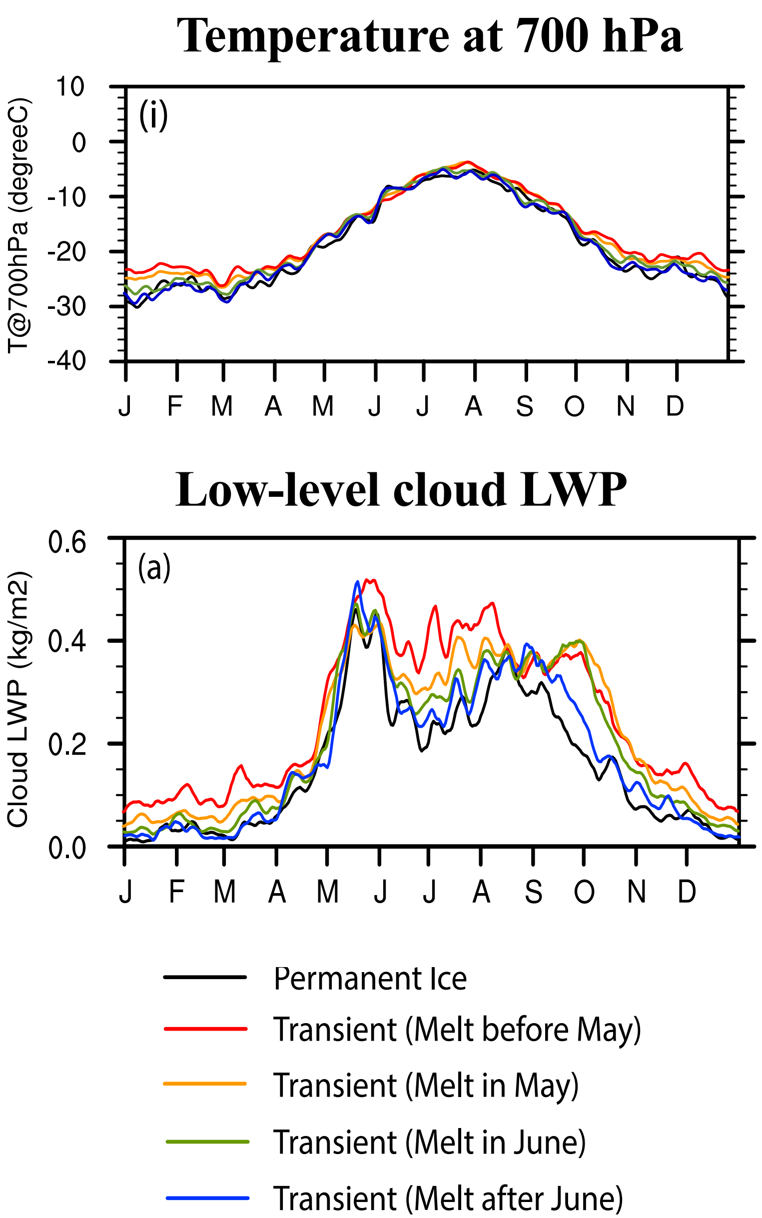
(2) The mid-summer increase in LTS ← the surface temperature becomes constant at $0^{o}C$ due to sea ice melt while the air temperature continues to warm.

(3) The LTS decrease from late summer to early autumn ← rapid cooling of the lower troposphere while the high thermal inertia of the water surface maintains a warmer surface skin temperature.

(4) The LTS increase in autumn ← the surface thermal inertia decrease caused by the sea ice freezing.

The timing of the LTS increase is highly dependent on the T_{sfc} change associated with sea ice variation!

Physical processes linking sea ice to the seasonal variations of low-level cloud LWP- Cloud microphysics



Cloud microphysical processes can also influence the seasonality of low-level cloud LWP due to temperature-dependent processes, where colder temperatures promote ice crystal formation and growth (Beesley and Moritz, 1999; Taylor et al., 2019).

However, our results suggest that **temperature-dependent cloud microphysics appears to not play a significant role in cloud LWP seasonality**:

- T_{700hPa} are similar across the different surface types.
- The warmest air temperatures do not align with the largest LWP values→ temperature dependent microphysics were a dominant factor to the summer cloud LWP variations.

SUMMARY

The Arctic low-level cloud liquid water path (LWP) seasonal cycle exhibits a surface-type dependence.

Sea ice melt onset affects the LWP PDF mainly in mid-summer; Sea ice freeze onset affects mainly the early fall maxima of cloud liquid water path and shift.

Sea ice affects LWP seasonality by modulating surface temperature and then lower tropospheric stability.

Thanks!

This work has been published as

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