Observations and Modeling of Polar Clouds: Cloud Links with Arctic Synoptic/Mesoscale "Weather" and Surface Conditions

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with contributions from many others
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Outline

Introduction: Cloud observational techniques; surface energy budget terms

Observations

Arctic cloud statistics-clouds prevail

Two main types of Arctic clouds, Sc and Ns: characteristics, environmental context

Formation mechanisms; moisture supply; thermodynamic/kinematic environments

Emphasize environmental Impacts: Cloud-Atmospheric BL-Surface system, esp. SEB

Modeling of clouds

Types: process; mesoscale, operational (reanalyses); regional, global climate

Validation

Process/mesoscale modeling issues:

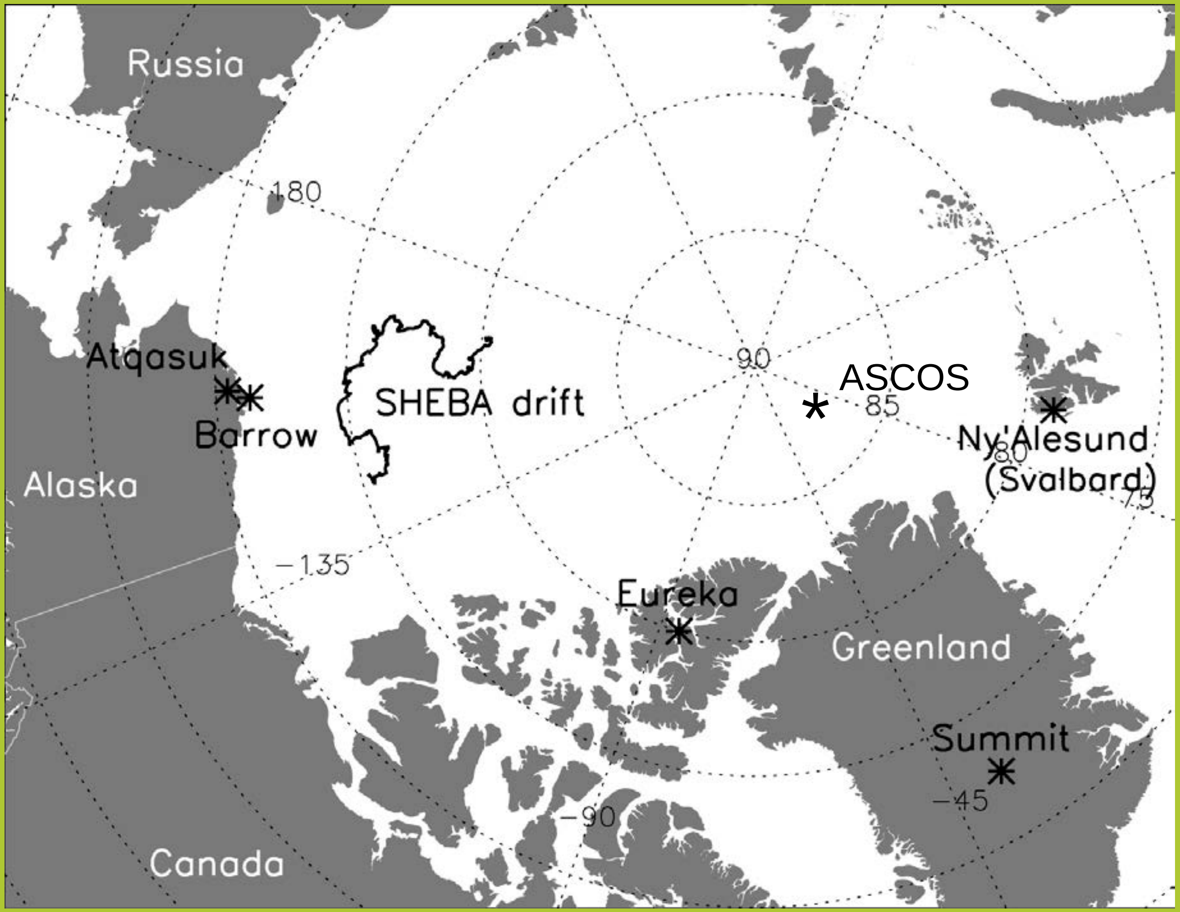
- Sc: supercooled LW (mixed phase); persistence; moisture source
- Ns: supercooled LW (mixed phase); dynamical formation?; moisture transport

Key deficiencies

Observational Sites for this Study

Land-based long-term observatories with extensive cloud observational capabilities: Barrow, Eureka, Ny Ålesund, Atqasuk, Summit

Ship/ice based observatories with extensive cloud-observational capabilities: SHEBA (10/1997-10/1998) and ASCOS (8/3/- 9/17/2008)

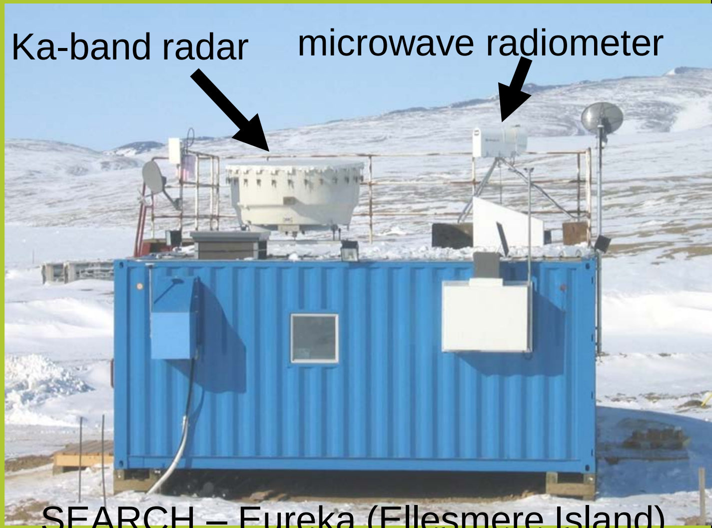


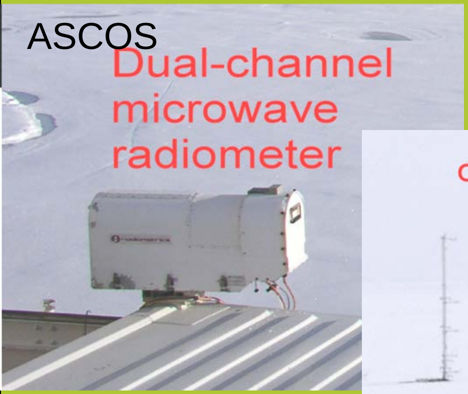
Remote sensing of cloud properties – macro/microphysical

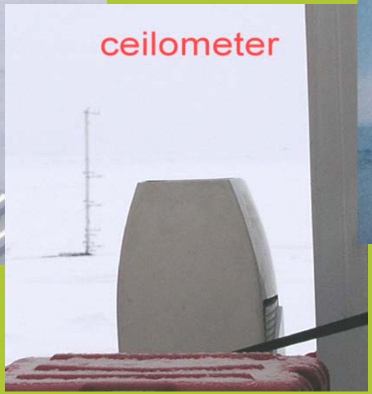
<u>Surface-based Remote Sensors</u>

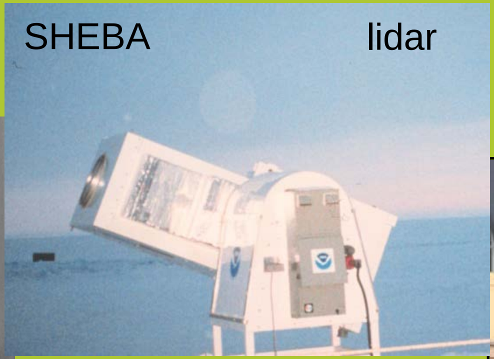
1) Ka-band (λ = 8 mm) cloud radar, dual-channel (24/31 GHz) microwave radiometer, ceilometer/lidar

- measure reflectivity, vertical velocity, spectral width, cloud base, brightness temperatures
- retrieve cloud properties, (cloud & precipitation boundaries, liquid water path, vertical air motion, liquid water content, ice water content, turbulence dissipation rate, cloud phase mask)
- ~30 s time scale, 0.1 – 12 km, Δz = 45 m



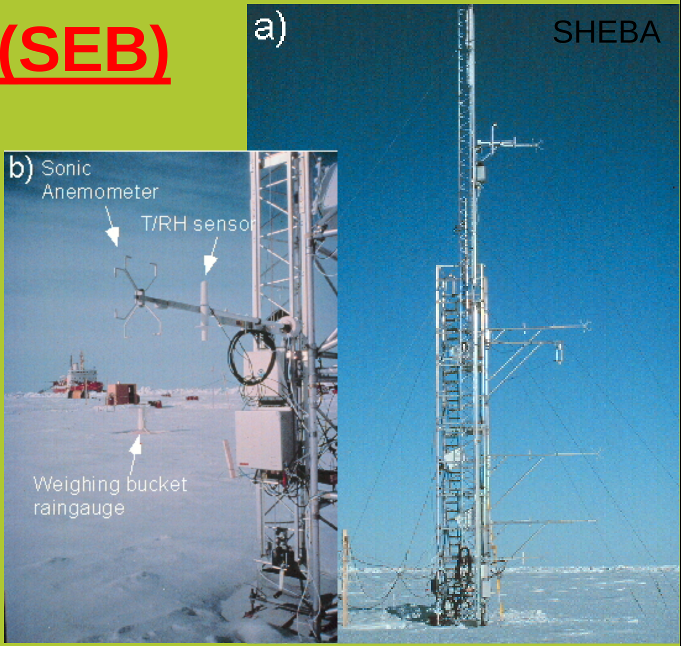






2) Extra-sensitive S-band (λ = 10 cm) cloud and precipitation radar (ASCOS)
- cloud macrophysical properties, reflectivity, vertical velocity, spectral width, precipitation rate

Surface Energy Budget (SEB)



- **SEB key relationship linking atmospheric processes to surface energy fluxes**

Net energy flux to surface, F_{net}

$$\mathbf{F_{net} = F_{atm} + F_o = Q_{net} - H_s - H_l + F_o} \qquad \mathbf{(1)}$$

$Q_{net} = SW_{net} + LW_{net} = SW_d - SW_u - SW_t + LW_d - LW_u$ – net radiative flux

$= SW_d\,(1-\alpha)\,(1 - f(D_s, D_i)\,) + \varepsilon_s(LW_d - \sigma T_s^4)$

$\alpha = SW_u/SW_d$ - albedo ; ε_s – emissivity of surface (~0.985 for snow)

SW_d, SW_u, LW_d and LW_u - downwelling/upwelling SW/LW rad. fluxes

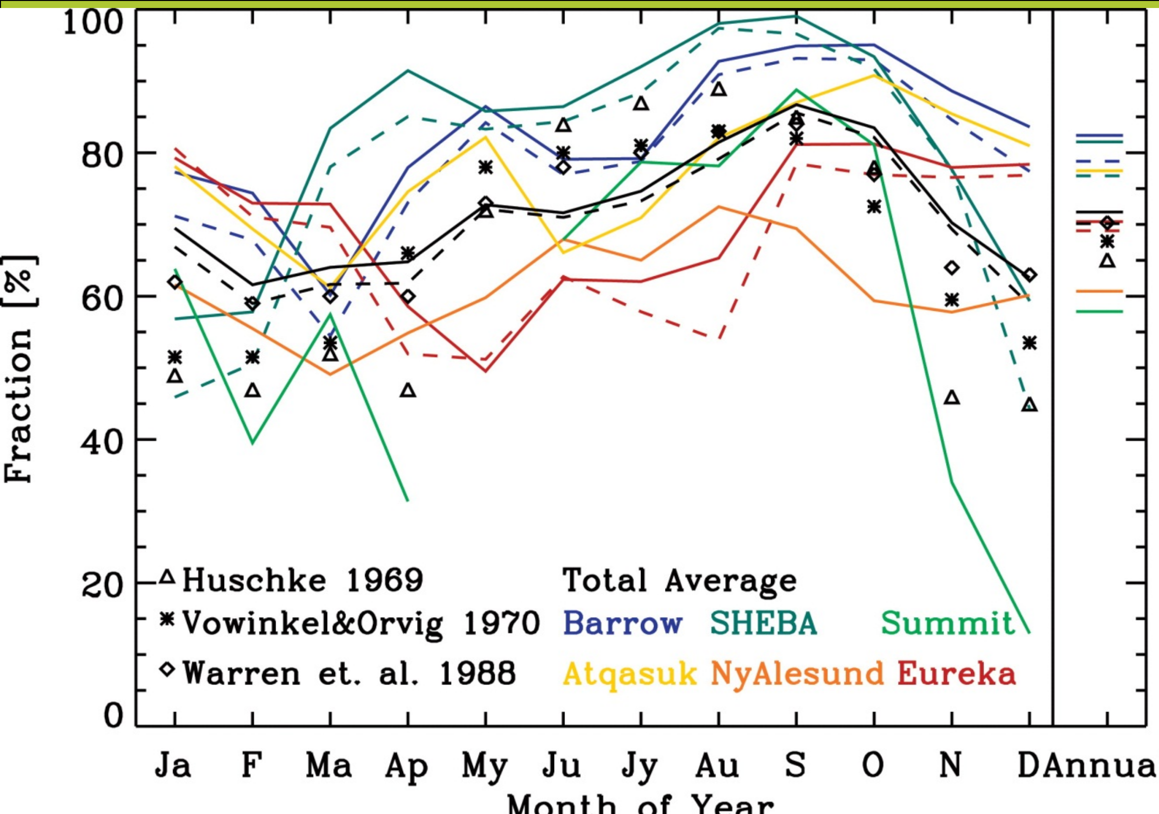
$SW_t = SW_d\,(1-\alpha)\,f(D_s, D_i)$ - shortwave radiation transmitted through surface (only applicable for sea ice)

H_s, H_l - turbulent sensible/ latent heat fluxes ($H_{turb} = H_s + H_l$)

F_o – surface conductive heat flux

$f(D_s, D_i)$ - shortwave extinction function dependent on snow (D_s) and ice (D_i) thickness

Clouds directly impact SW_d , LW_d, and α, indirectly impact all of the other terms (e.g., H_s, H_l, F_0) through system responses given by SEB (eqn 1).



Arctic Cloud Statistics

Shupe et al 2011 (JAMC)

Cloud Fraction

- sites with multiple-year remote sensing observations (Barrow, Atqasuk Eureka, Ny Ålesund; 5-12 yrs) or one full year (SHEBA and Summit).

Annual cloud fraction 58%-83% (site avg. 72%):
- least at Summit (58%) and Ny Ålesund (61%)
- greatest at Barrow (83%) and SHEBA (82%)
- historical climatologies 65%-70%

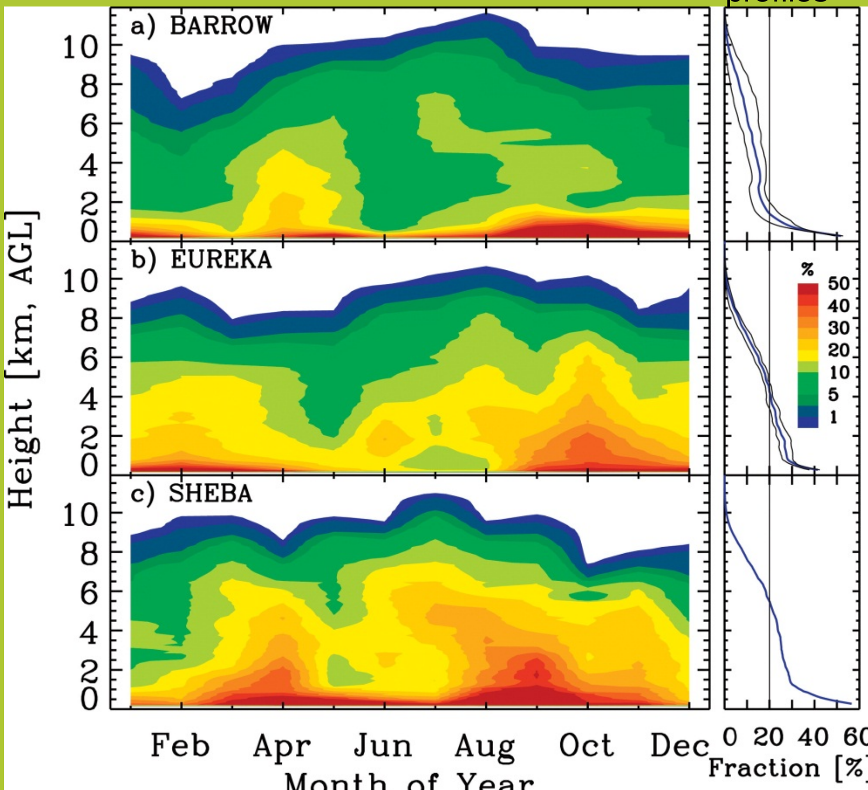
Annual variability
- min. in winter (DJF) 61-70%;
- max. in late summer/autumn (ASO) 81-86% (92-99% at BRW & SHEBA)
- Eureka exception: min in spring/early summer; max – autumn/winter

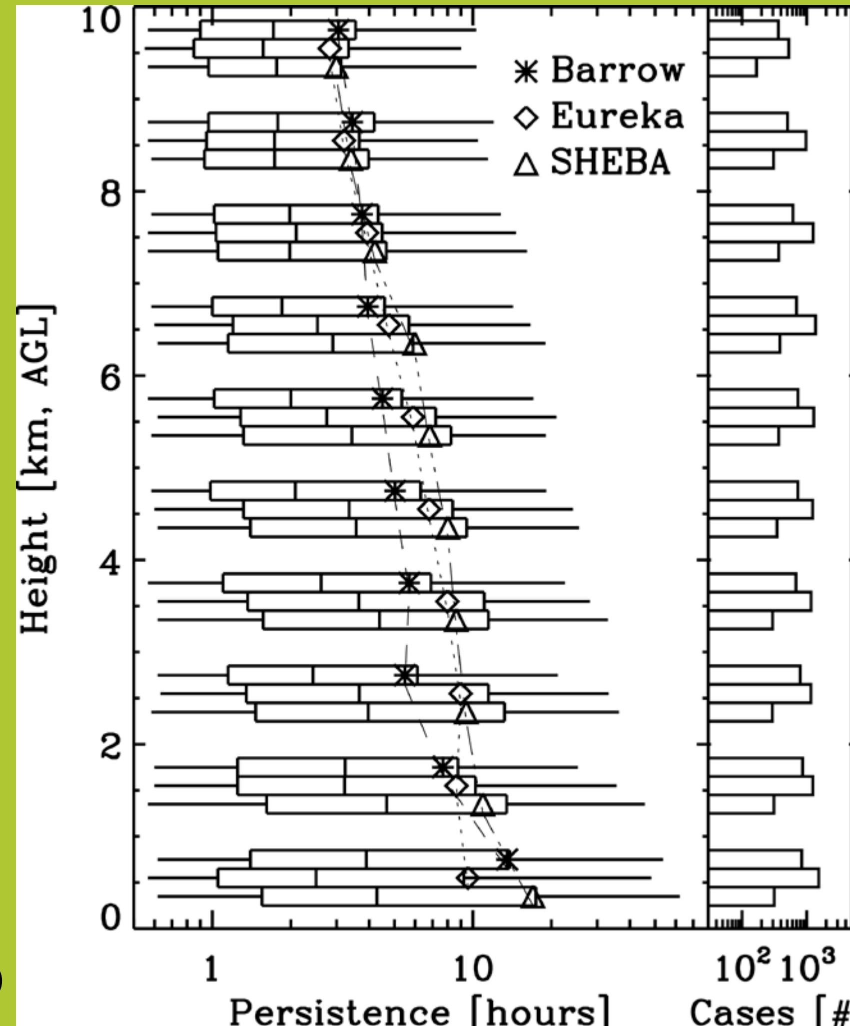
Height Distributions of Arctic Cloud Statistics

Shupe et al 2011 (JAMC)

- cloud fraction and cloud persistence (< 0.5 h gaps)
- sites with cloud radar or lidar

Annual Mean profiles





1) High frequency of low clouds (<1.2 km) at all 3 sites (40-55% of time)
2) Low clouds most frequent Aug-Nov at Barrow and SHEBA and Sep-Mar at Eureka
3) Mid-level clouds (2-6 km) least frequent at Barrow (2-20% of time) and most frequent at SHEBA (15-35% of time)
4) Mid-level clouds most frequent in late summer/autumn and Mar-Apr (BRW, SHEBA) or Sep-Mar (EUR)

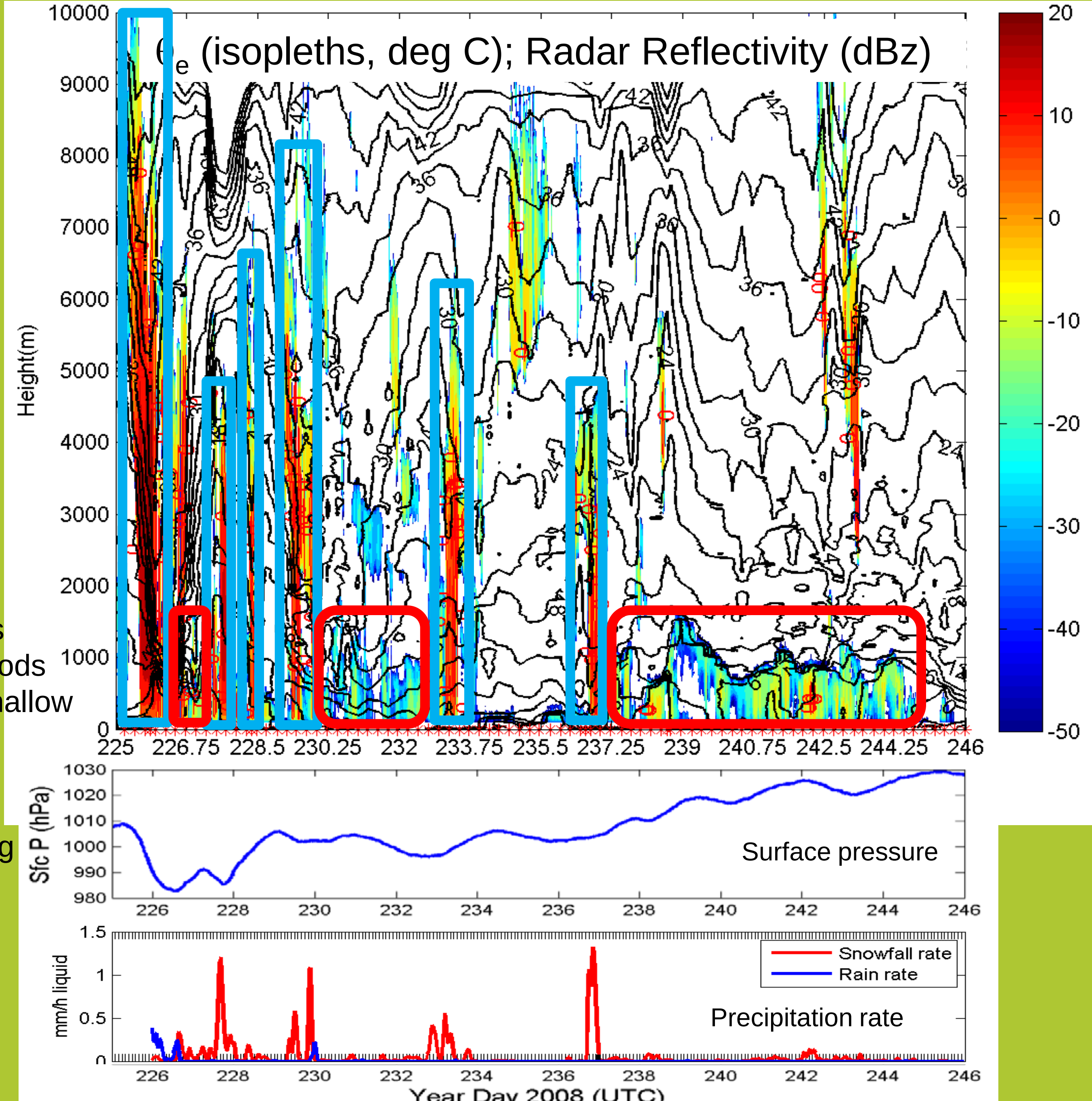
Median 75% 95%

1) Low clouds most persistent (2.5-4.5 h; 10-18 h; 50-65 h)
2) Mid-level clouds more transitory (2.5-4.0 h; 7-10 h; 20-30 h) (frontal time-scale?)
3) High frequency of low clouds due to greater persistence

ASCOS
87.5° N
Aug 12 -Sep 1, 2008
Icebreaker Oden

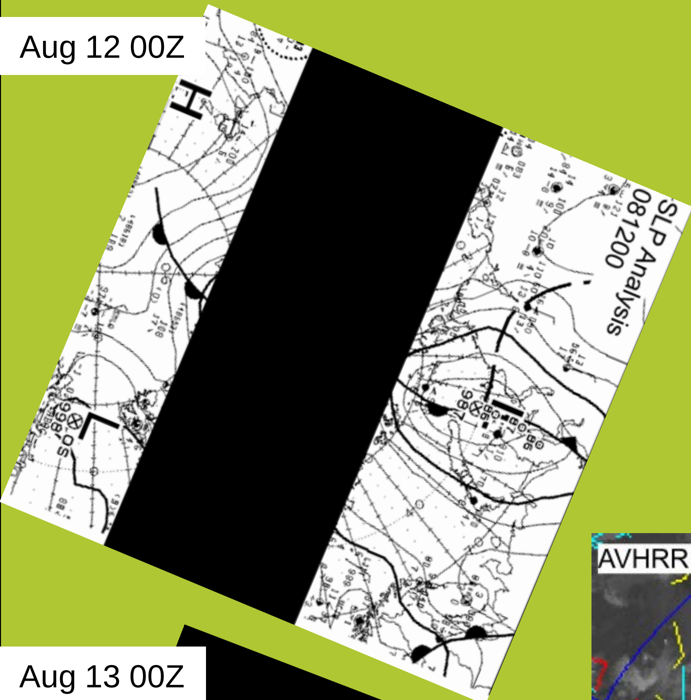
Ns clouds (1st half of exp.)
- deep, often precipitating
- significant press troughs
- formed by dynamics with mesoscale/synoptic cyclones and/or fronts

Sc clouds
- interspersed between storms
- can persist for extended periods
- low-level (0.5-1.5 km) and shallow
- light or no precip
- high pressure
- formed and maintained by cloud-top radiative cooling



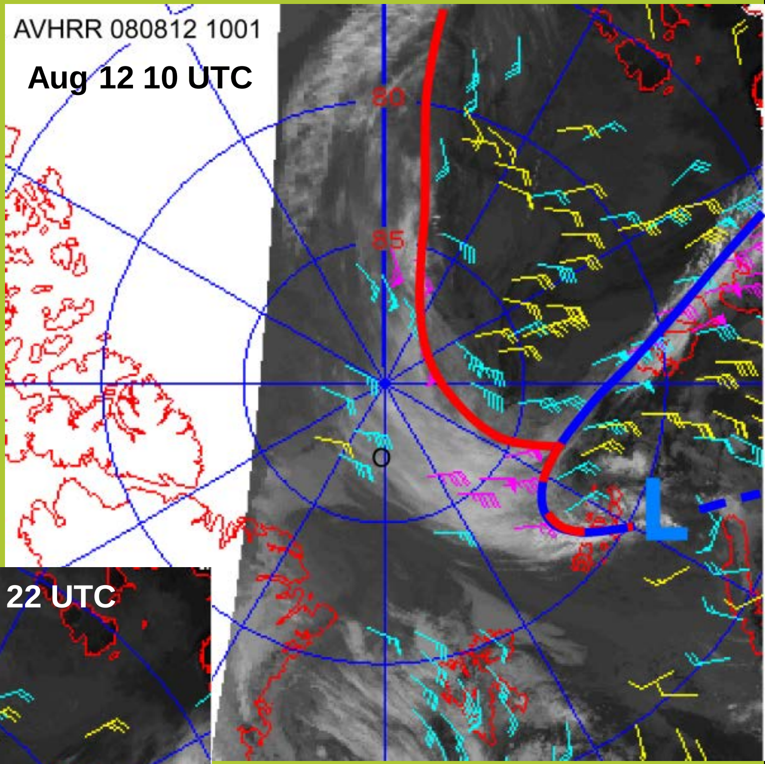
ASCOS Storm Case, Aug 12-13, 2008

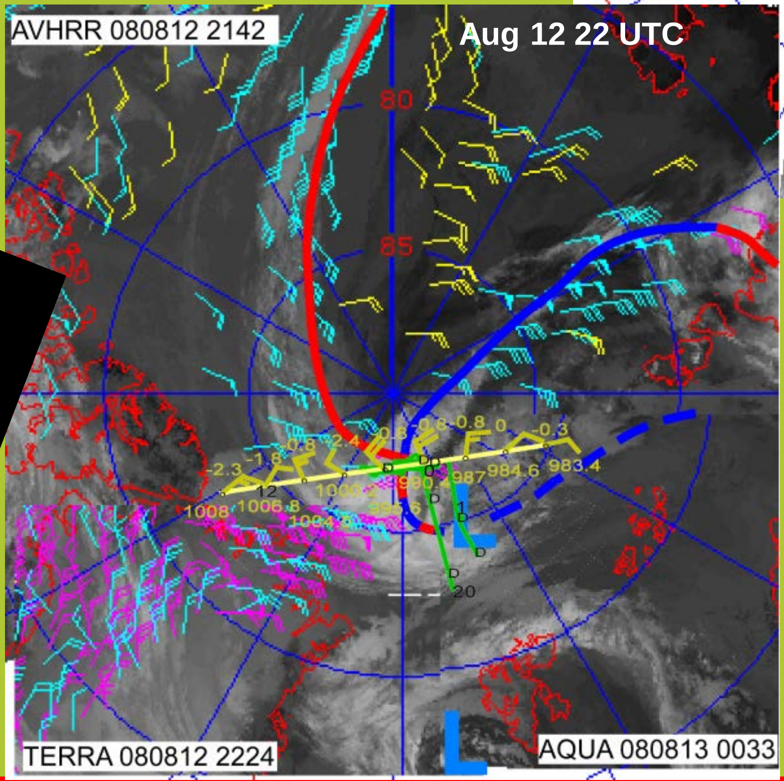
Aug 12 00Z



Aug 13 00Z

Canadian Weather Service sea-level pressure analyses at a) 00 UTC Aug. 12, b) 12 UTC Aug. 12, c) 00 UTC Aug. 13, and d) 12 UTC Aug. 13. The Oden is the reporting station at 87.5° N, 2° W.





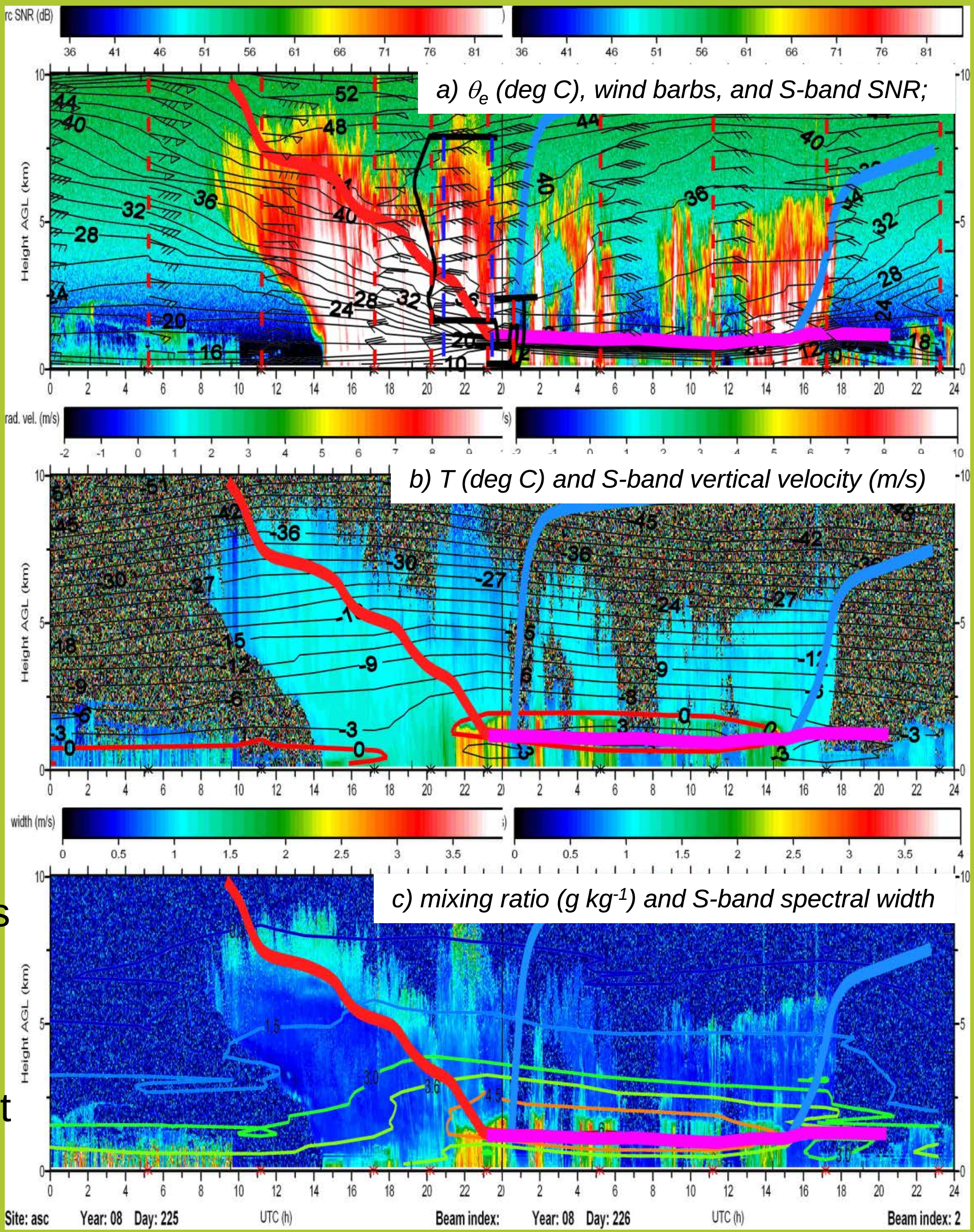
Sequence of AVHRR satellite images showing the synoptic evolution. The satellite-derived winds and the surface frontal features are shown in each image. The tracks of the DC-8 (green) and Oden (yellow) are shown in b) using a system phase velocity of 14.5 m s^{-1} from 81°.

Linking Storm Clouds to Thermodynamic/Kinematic Structure

ASCOS, Aug. 12-13, 2008

Time-height cross section of a) θ_e (deg C), wind barbs, and S-band SNR; b) temperature (deg C) and S-band vertical velocity; and c) mixing ratio (g kg^{-1}) and S-band spectral width.

Each panel is overlaid with a frontal analysis based primarily on θ_e (heavy red, blue, and purple lines), theDC-8 flight track data (heavy black line), radiosondes (red stars on abscissa & vertical dashed lines), and dropsondes (vertical dashed blue lines). The heavy red isopleth in b) is the 0° C isotherm, and the heavy magenta line shows the location of a strong inversion.



Main Points

1) Classical occluded frontal system, with warm/moist advection in narrow warm sector above surface inversion
2) Post-frontal warm air separated from surface by inversion
3) Deep clouds and precipitation primarily associated with warm-front
4) Elevated warm-air advection producing period of surface freezing rain and sleet
5) Turbulence near top of warm-frontal clouds likely producing convective generating cells for warm-frontal precipitation and possibly supercooled liquid water
6) Classical occluded frontal structure (except low-level inversion); clouds dynamically forced

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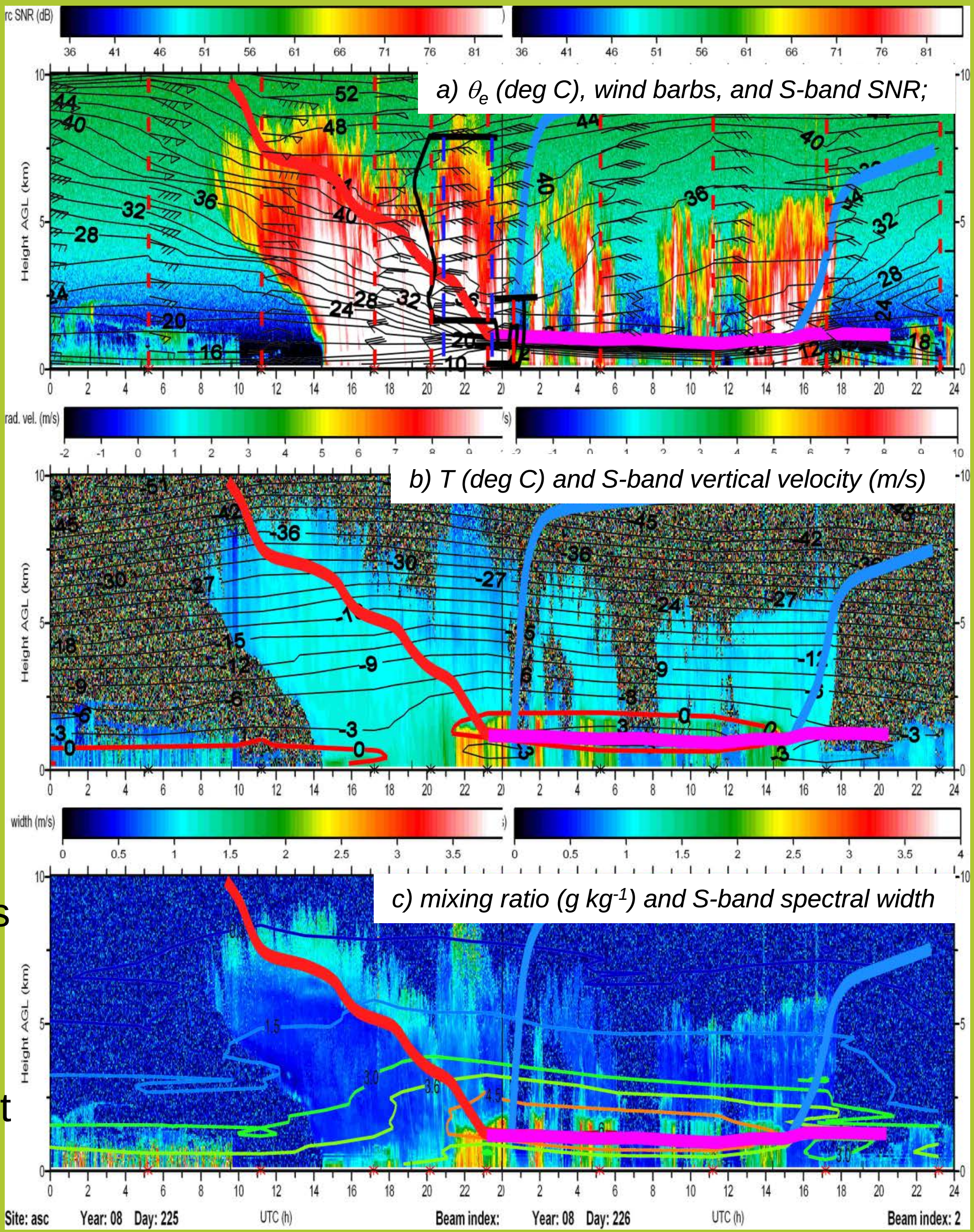

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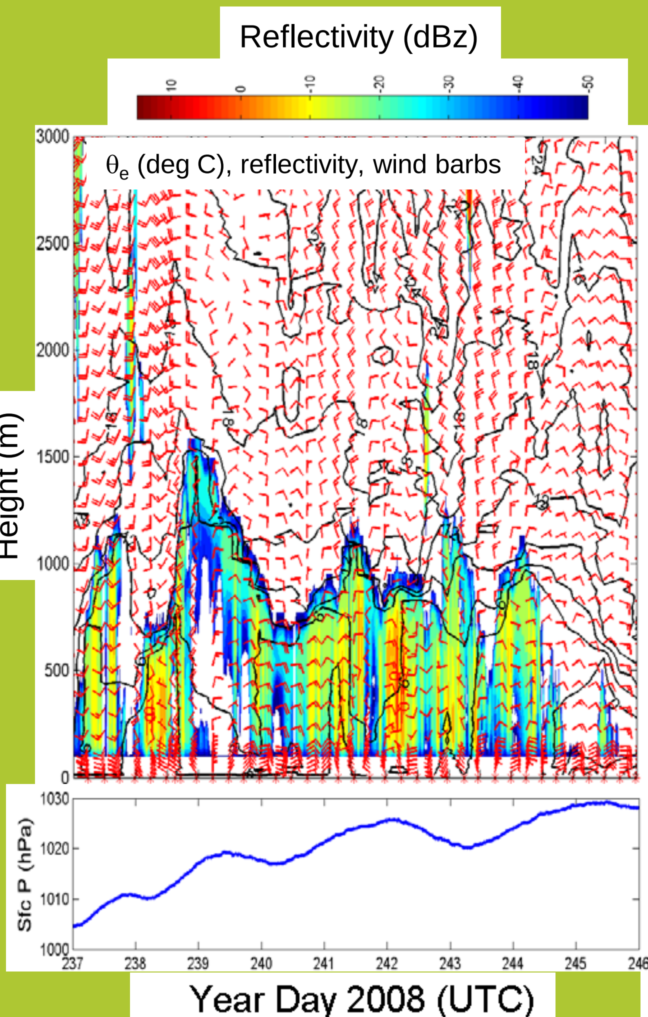
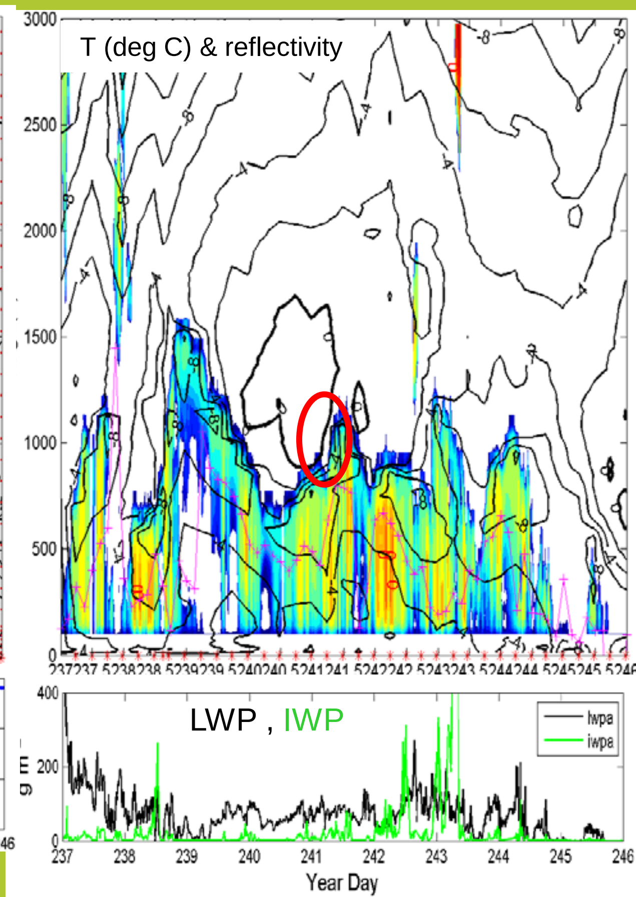
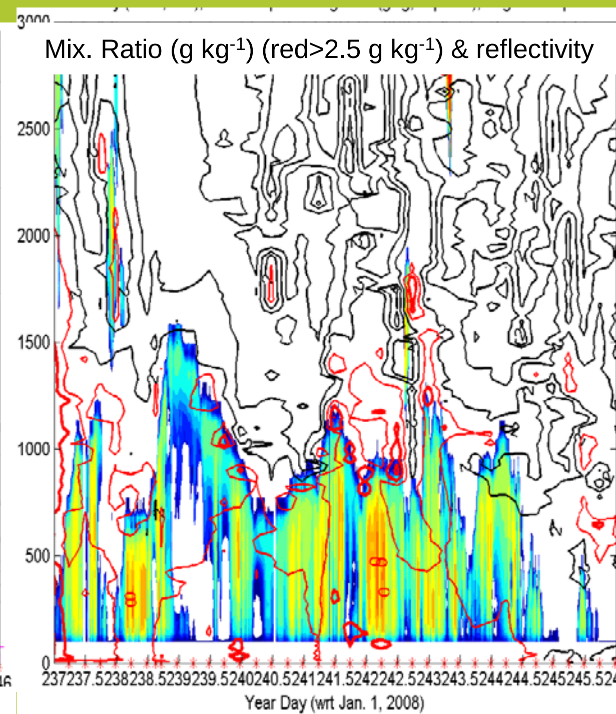
TD/kinematic environment for Sc (ASCOS, Aug 24- Sep 1, 2008)







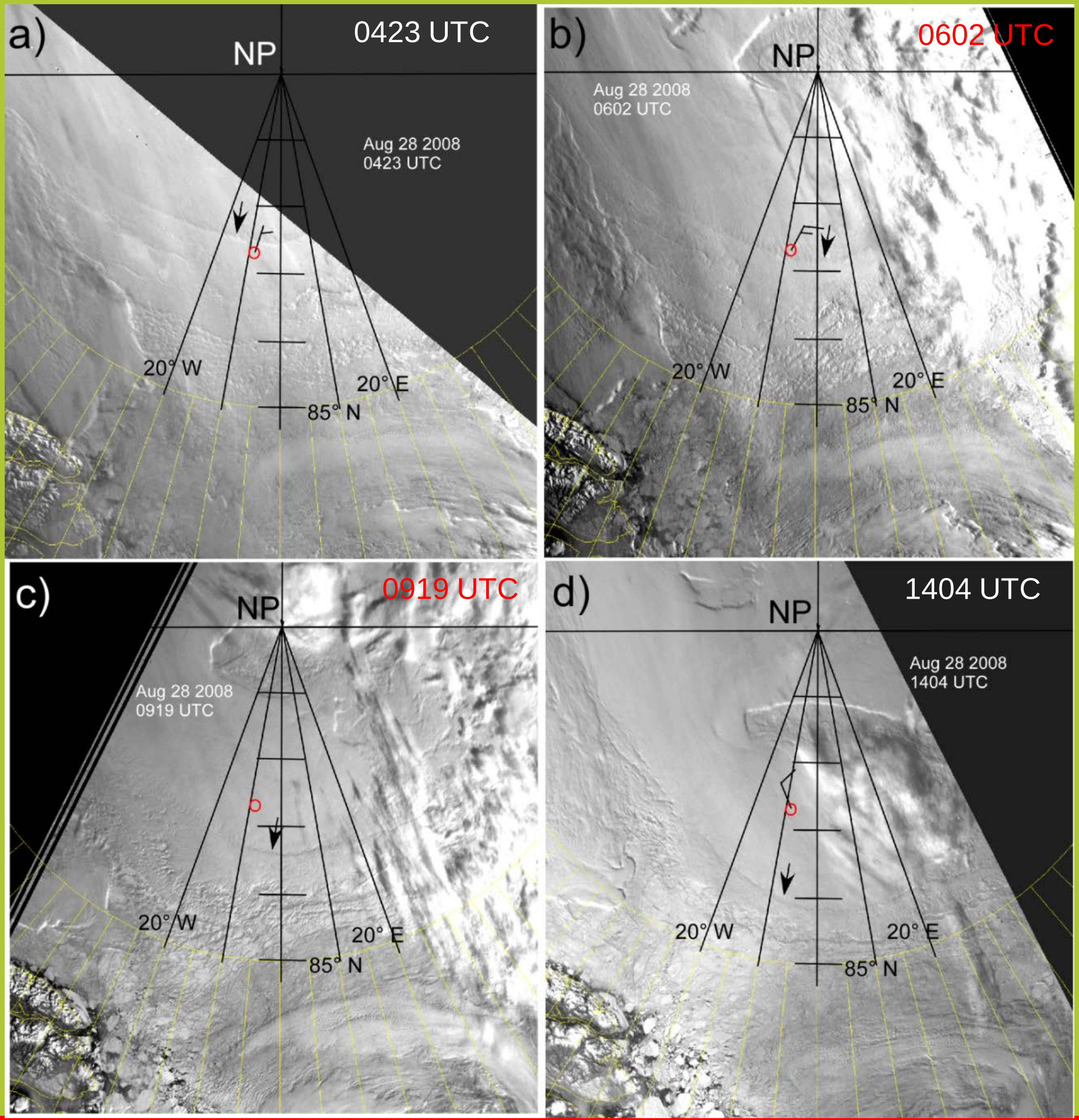
Weak θ_e gradients
High/rising surface pressure
Some variability in winds and sfc pressure
Near-neutral stability within cloud, with occasional near-surface stability – cloudtop-surface coupling/decoupling
Processes modulating cloud top height & coupling/decoupling not fully understood

T ~ -9 - -8 °C at cloud top and ~ - 2 °C at sfc
Mixed phase cloud, with LWP ~ 20-200 g m^{-2} and IWP ~ 1 - 300 g m^{-2}
LW important for radiative effects
Strong T inversion at cloud top, with occasional T > 0 °C above cloud
Cloud in top 200-400 m of reflectivity region

Water vapor inversion often seen with T inversion at cloud top
- significant for cloud formation & persistence
- unique for Arctic Sc compared to subtropical Sc

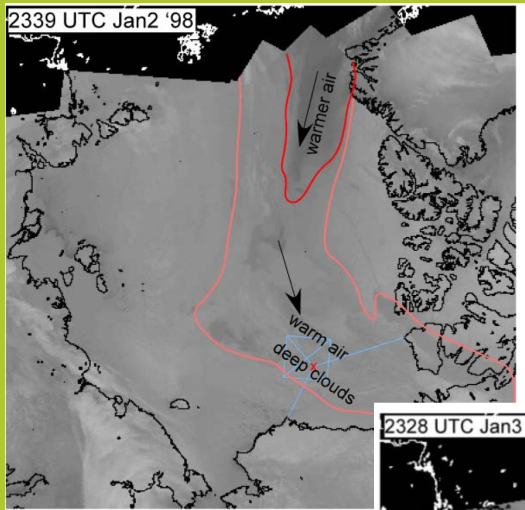
Visible images of Sc clouds on morning of Aug 28 (YD 241.2 – 241.6)

- illustrate extensive scale of clouds and advective nature of character changes
- 300-400 m lifting of Sc top at 06 UTC associated with advection of 300-400 km arced feature

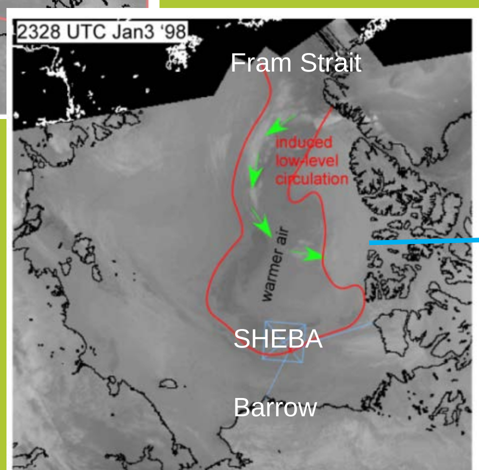


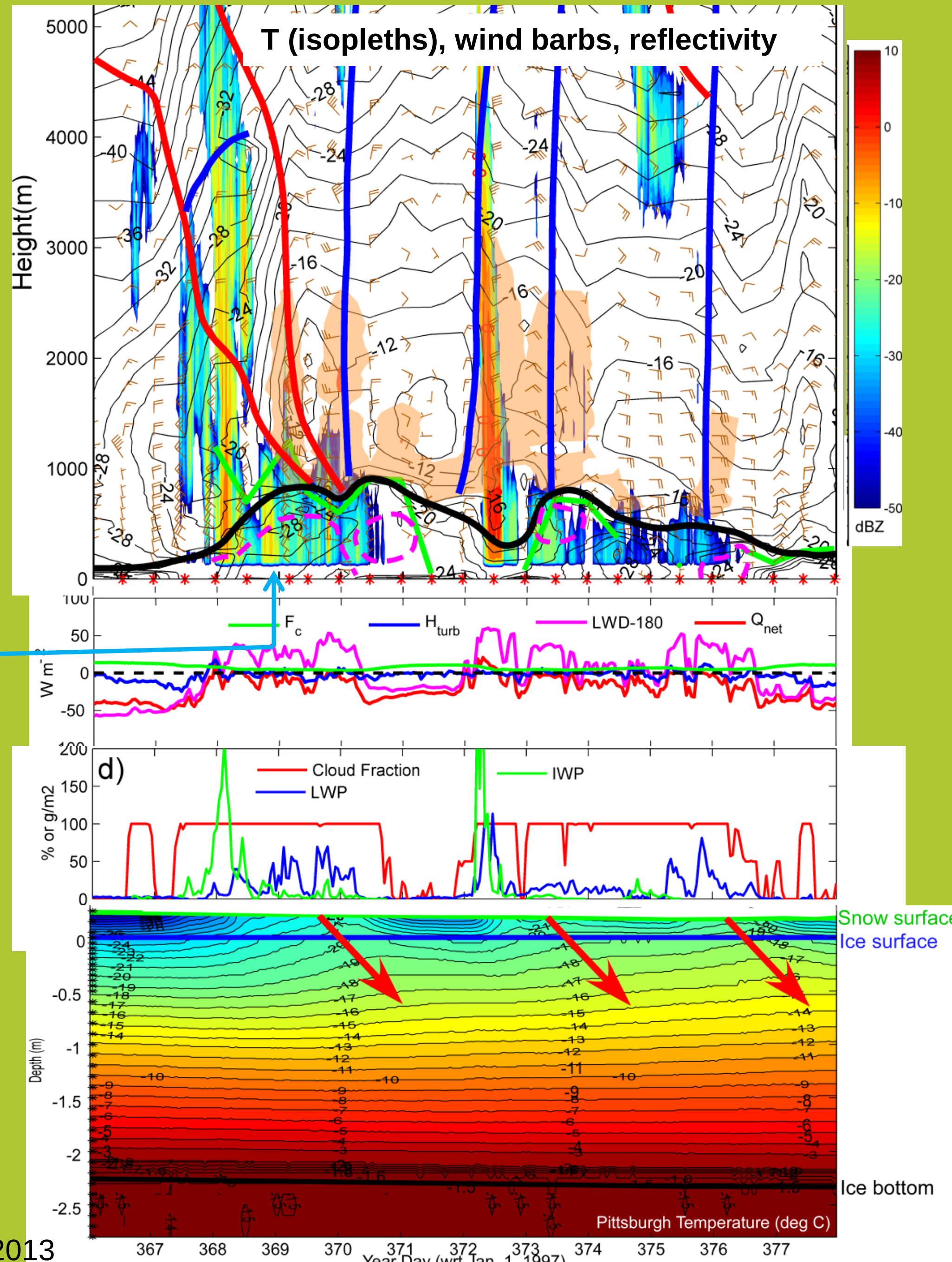
Images provided by Dundee Satellite Service

SHEBA Jan. 1-12, 1998; Beaufort Sea



IR satellite images





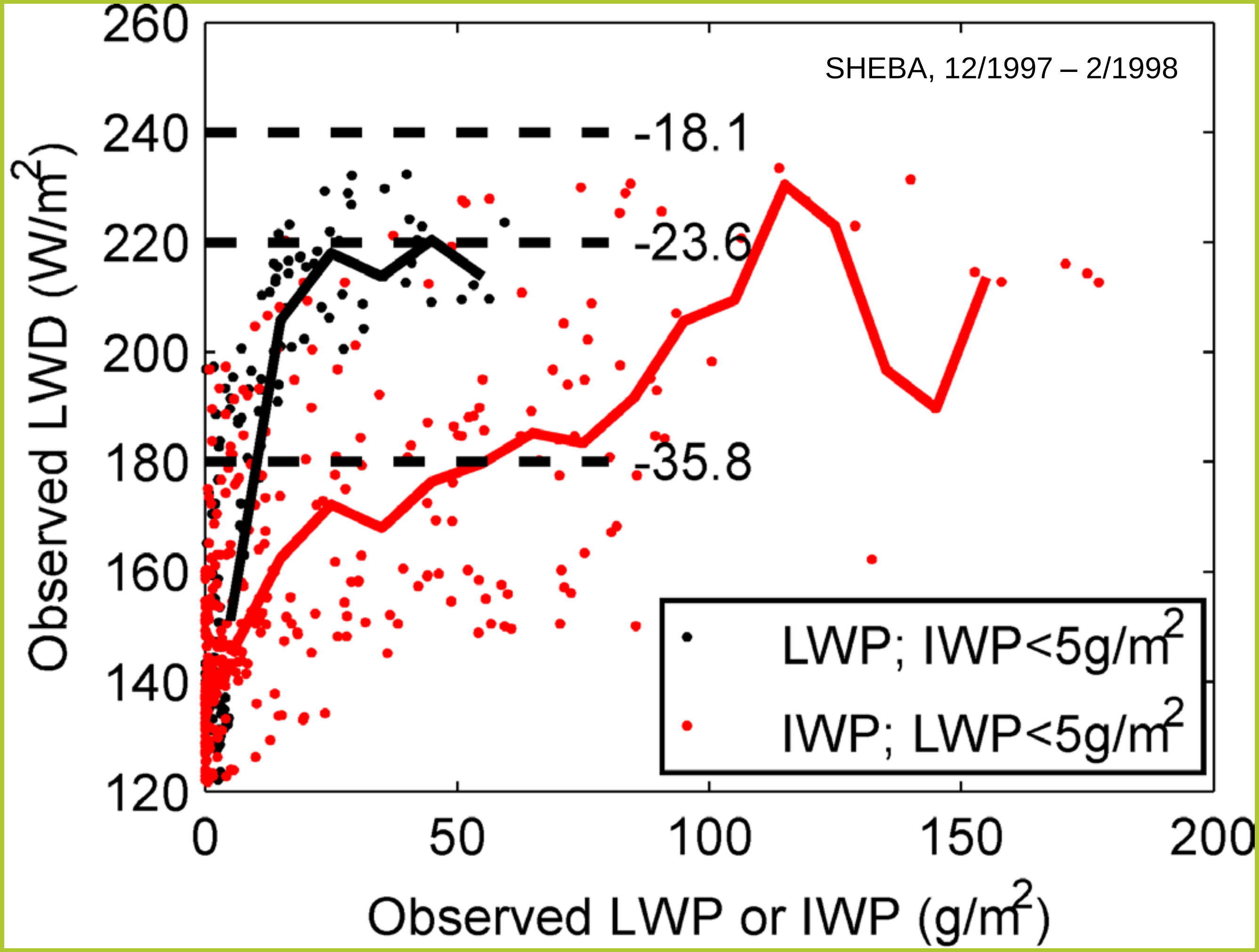
1) Long-distance free tropospheric advection of heat and moisture significant

2) Associated clouds (esp. with liquid) have strong impact on LW_d, F_{net}, and T_s

3) Thermal structure in snow and ice respond strongly to synoptic/mesoscale atmospheric events and presence of liquid water in clouds

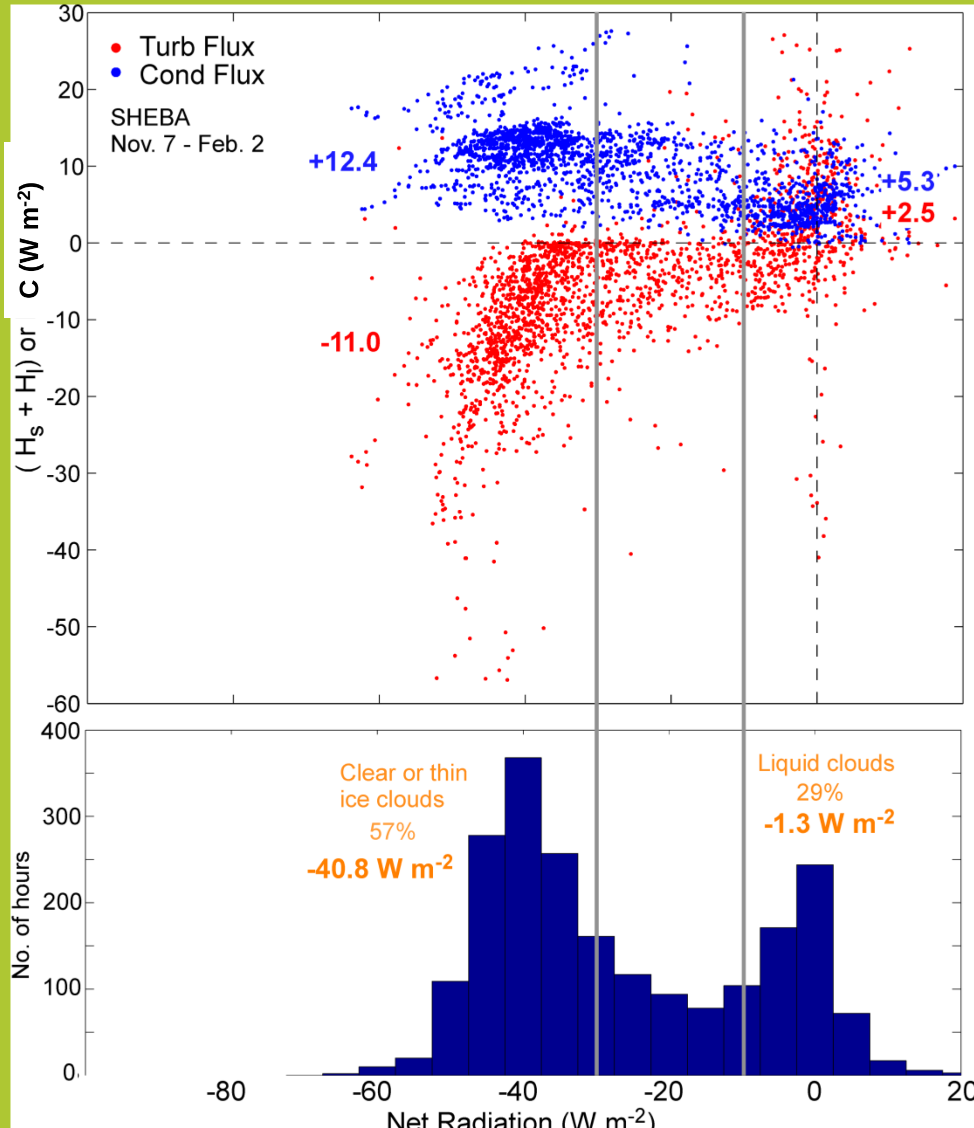
Persson et al 2013

Sensitivity of LWD to LWP and IWP



Observed Responses to Radiation Changes over Arctic Sea Ice

SHEBA Polar Night (Nov. 7, 1997 – Feb. 2, 1998; No solar radiation)
Beaufort Sea – Multi-year Arctic sea ice



Observations clearly show clouds and CLW also impact H_s + H_l and F_0

Process Relationships:

$F_{net} \approx LW_{net} - (H_s + H_l) + C$;

$H_s + H_l$ vs LW_{net}, C vs LW_{net}

Clear skies
- surface warmed by both H_s+H_l and C
- F_{net} ~ -17.5 W m^{-2}

Cloudy skies (with liquid water)
- both C & H_s+H_l respond to LW_{net} increase by -7.1 W m^{-2} and +13.5 W m^{-2}, respectively
- surface warmed by C but cooled by H_s + H_l
- F_{net} ~ +1.5 W m^{-2}

Modeling of Polar Clouds

Process models (nested WRF, classical LES, single-column models)

Sc clouds
- how to improve microphysical structure?
- how to improve radiative impacts?
- understand moisture supply and cloud persistence
- aerosol impacts

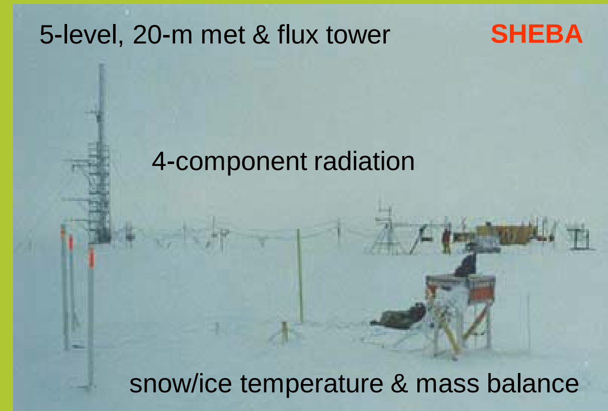
Validations of:

Mesoscale/Forecast Models, Reanalyses (WRF, ERA40, ERA-I)

Regional (large suite) and Global Climate Models (CCSM4)

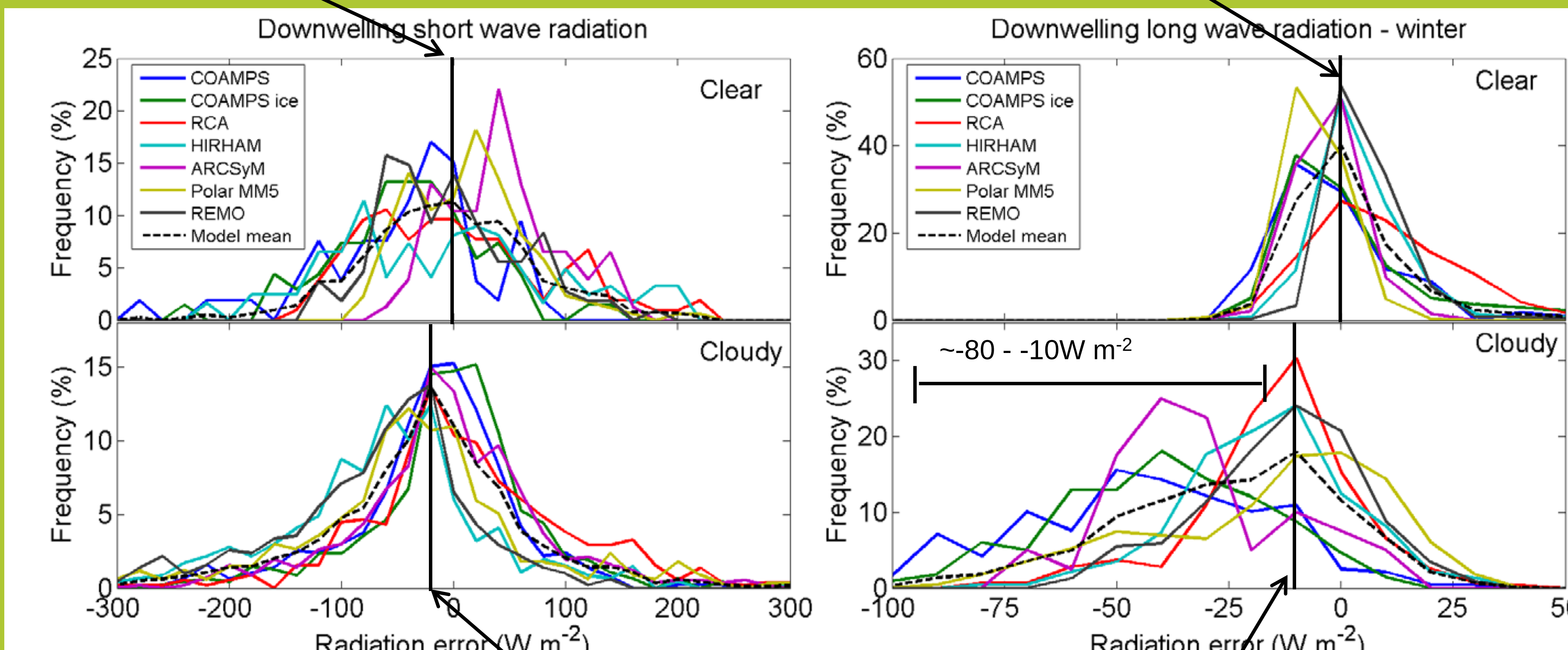
SHEBA Data

- only year-round, comprehensive, atmospheric data set over sea ice
- extensively used; e.g., validation of regional climate models



~ 0 W m^{-2}, uncertain

~ 0 W m^{-2}

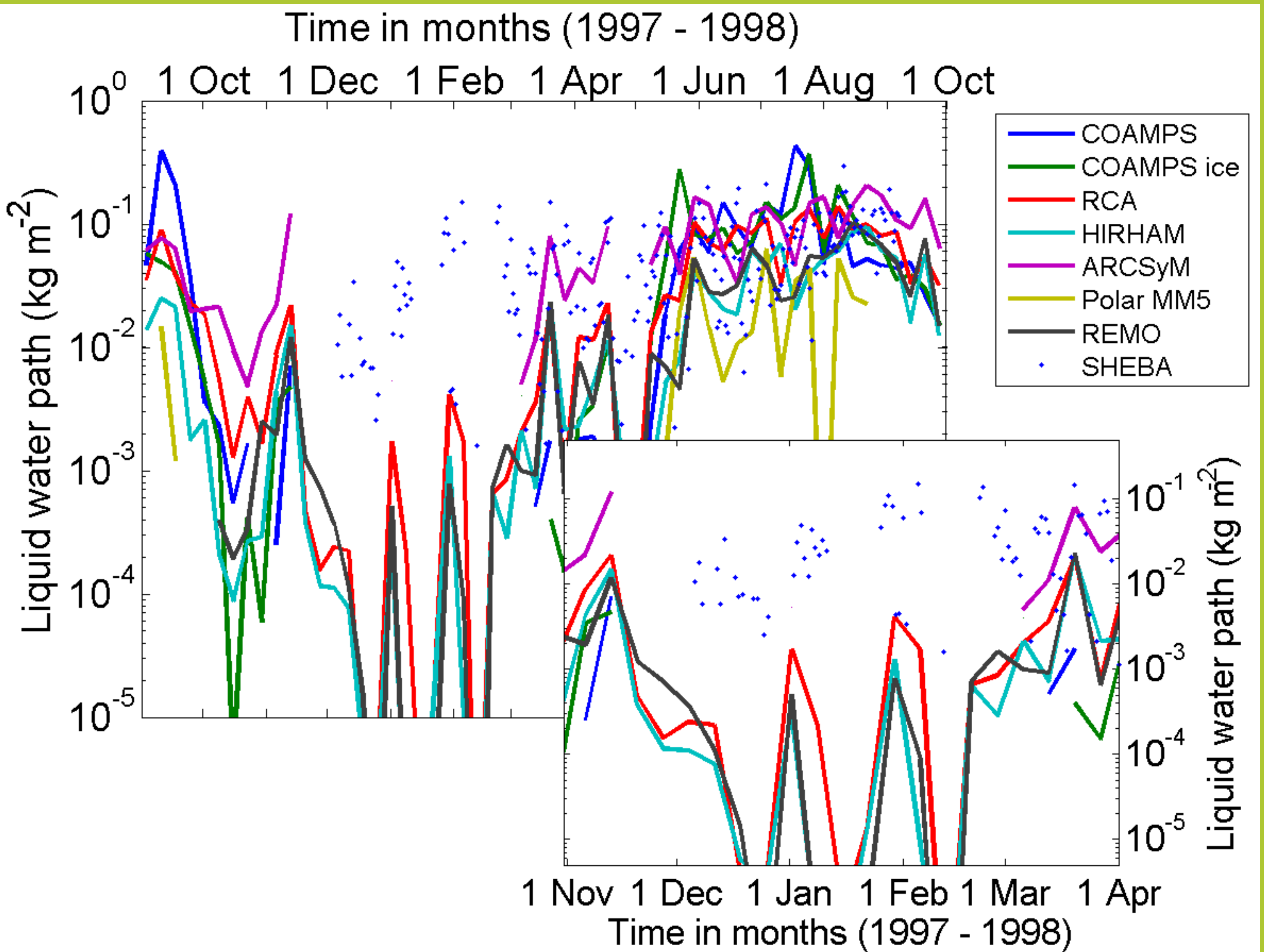


~-30 W m^{-2}

~-10 W m^{-2}

Tjernström et al. 2008

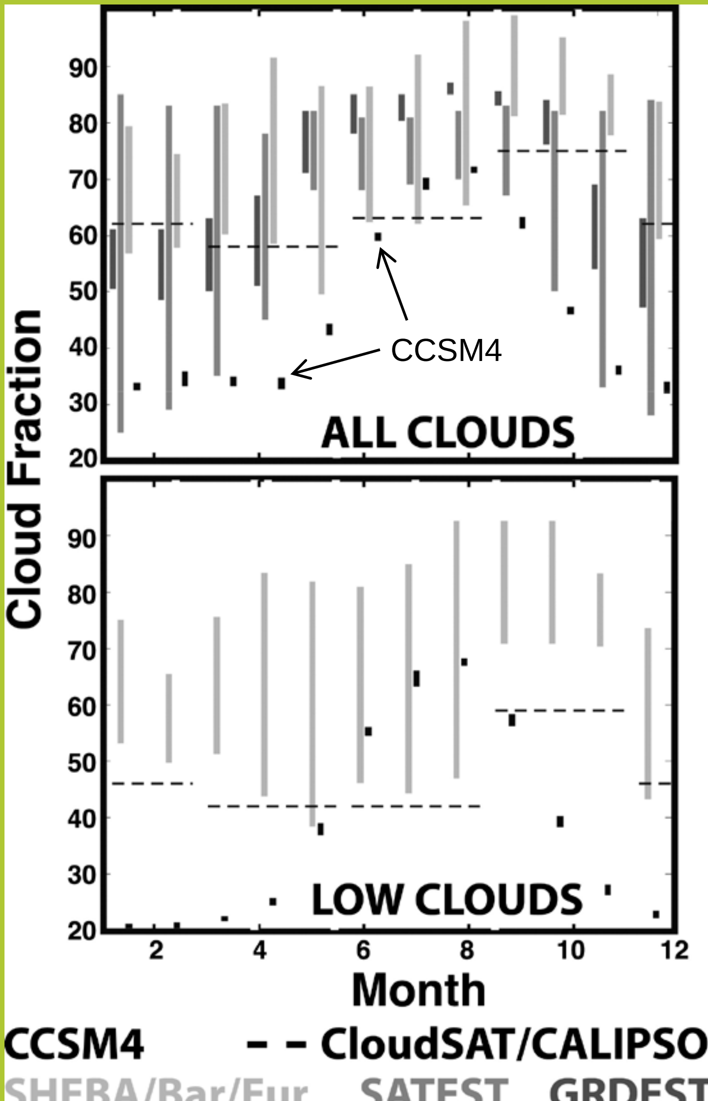
Regional Climate Model Validation of LWP



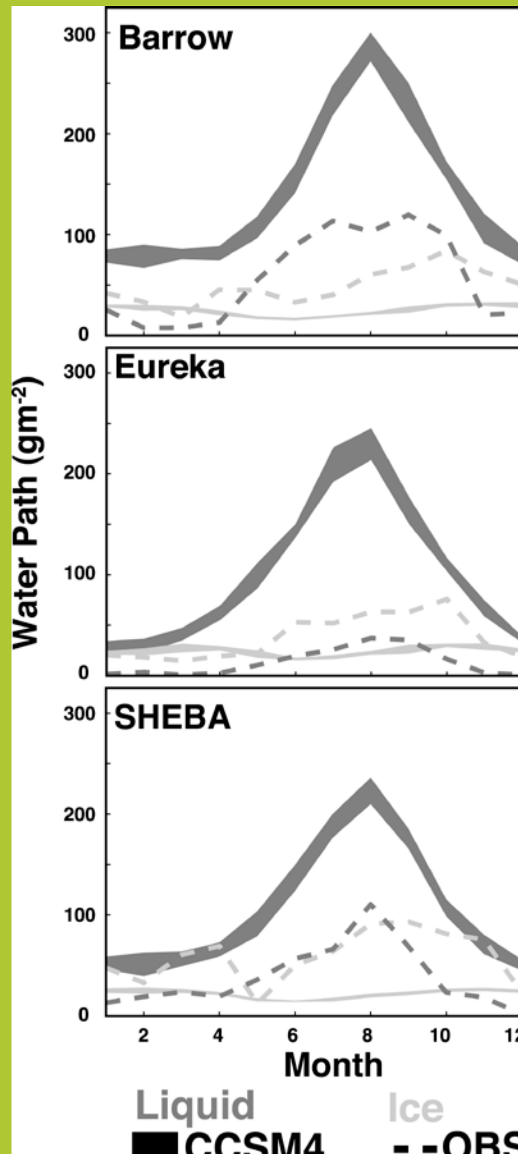
Prenni et al. 2006

Global Climate Model CCSM4 Cloud validation

CCSM cloud fraction for the entire Arctic region (70°–90°N) plotted with estimates of cloud fraction from several satellite and ground-based sources (see text for details). Comparisons are included for (top) all clouds and (bottom) low clouds only



CCSM4 (shading) and observationally derived (dashed-lines) all-sky liquid (darker) and ice (lighter) water paths for three observation sites.



In CCSM4

a) Cloud fraction much too small, especially for wintertime low clouds

b) LWP too large and IWP too small

CCSM4 has problems forming and/or maintaining clouds, especially low-level wintertime clouds, but it has too much liquid and too little ice when they do form

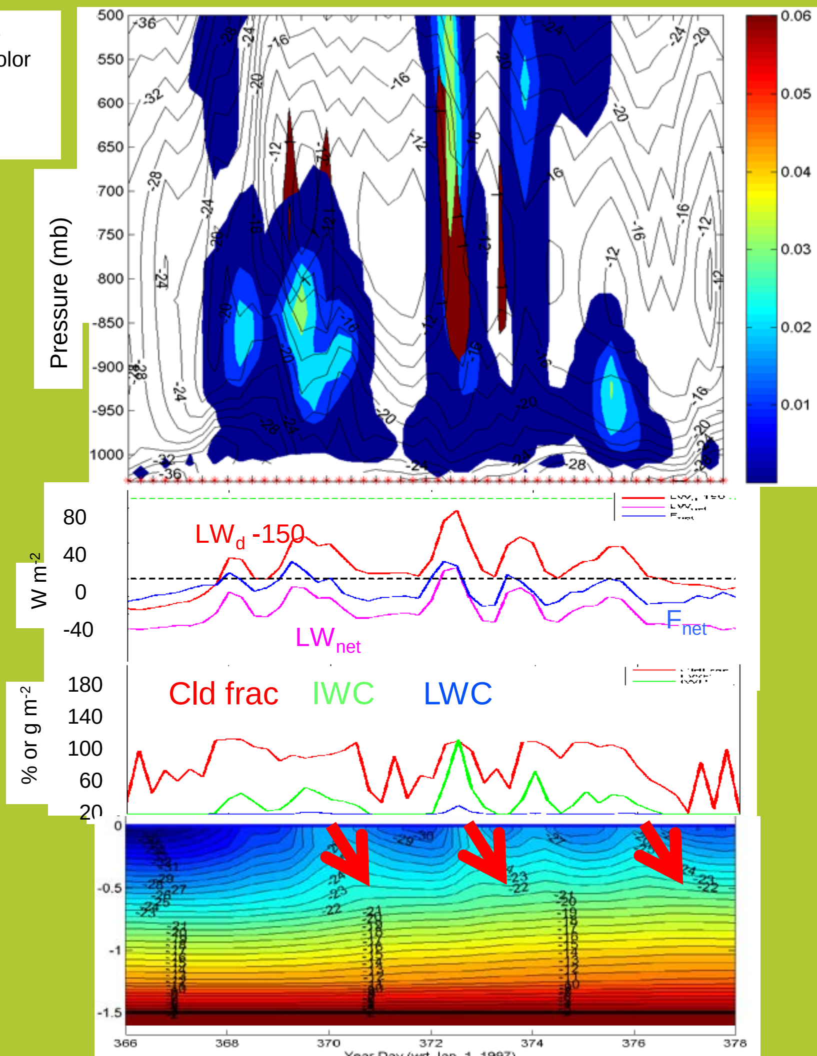
(deBoer et al 2012)

ERA40 analysis of SHEBA January Case:

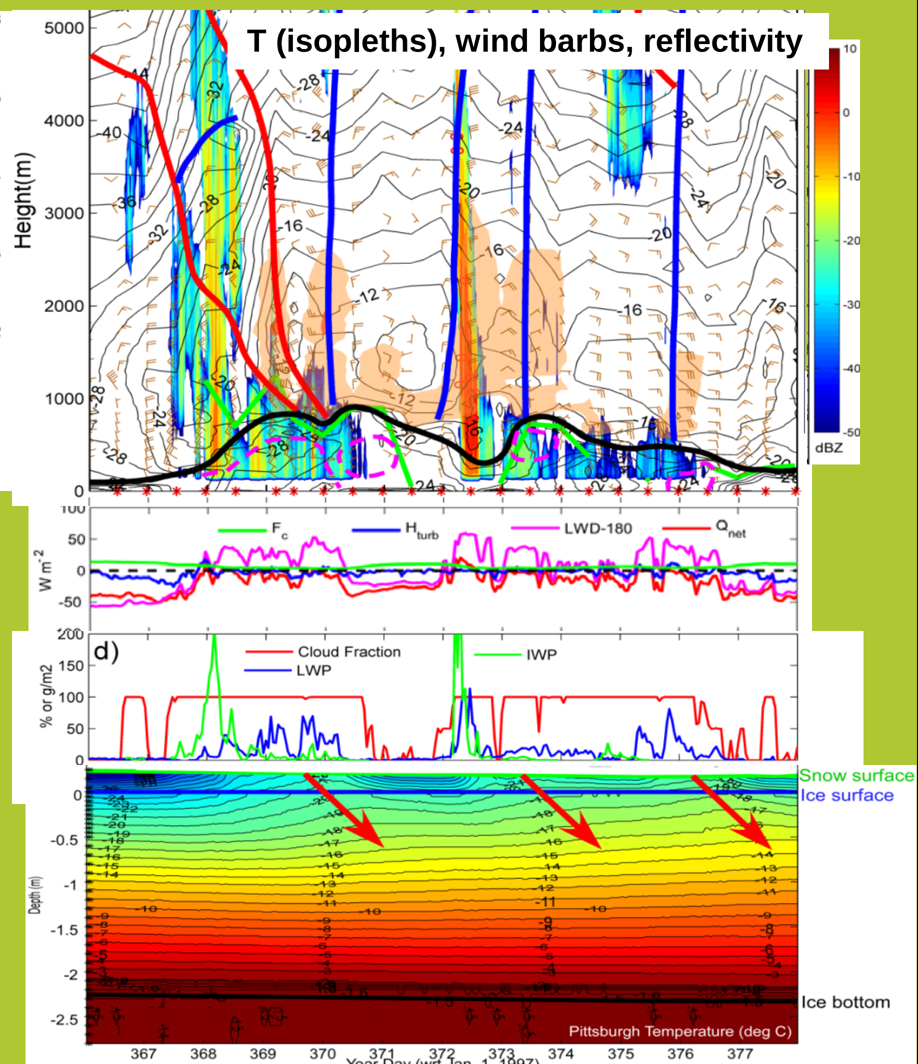
a) Cloud ice peak matches observed deep cloud time; b) LW_d not as consistently elevated as in obs; c) Q_v maximum (> 1 g/kg brown) arrives with warm air as in obs, but ~ 0.5 g/kg less ; d) Very little liquid water in ERA40!; e) No snow cover and assumed 1.5 m thickness produces more rapid thermal wave penetration and heat loss, and larger in-ice thermal gradients.

ERA40

ERA40: Cloud ice concentration – color
Temperature – isopleth
Q_v >1 g/kg brown

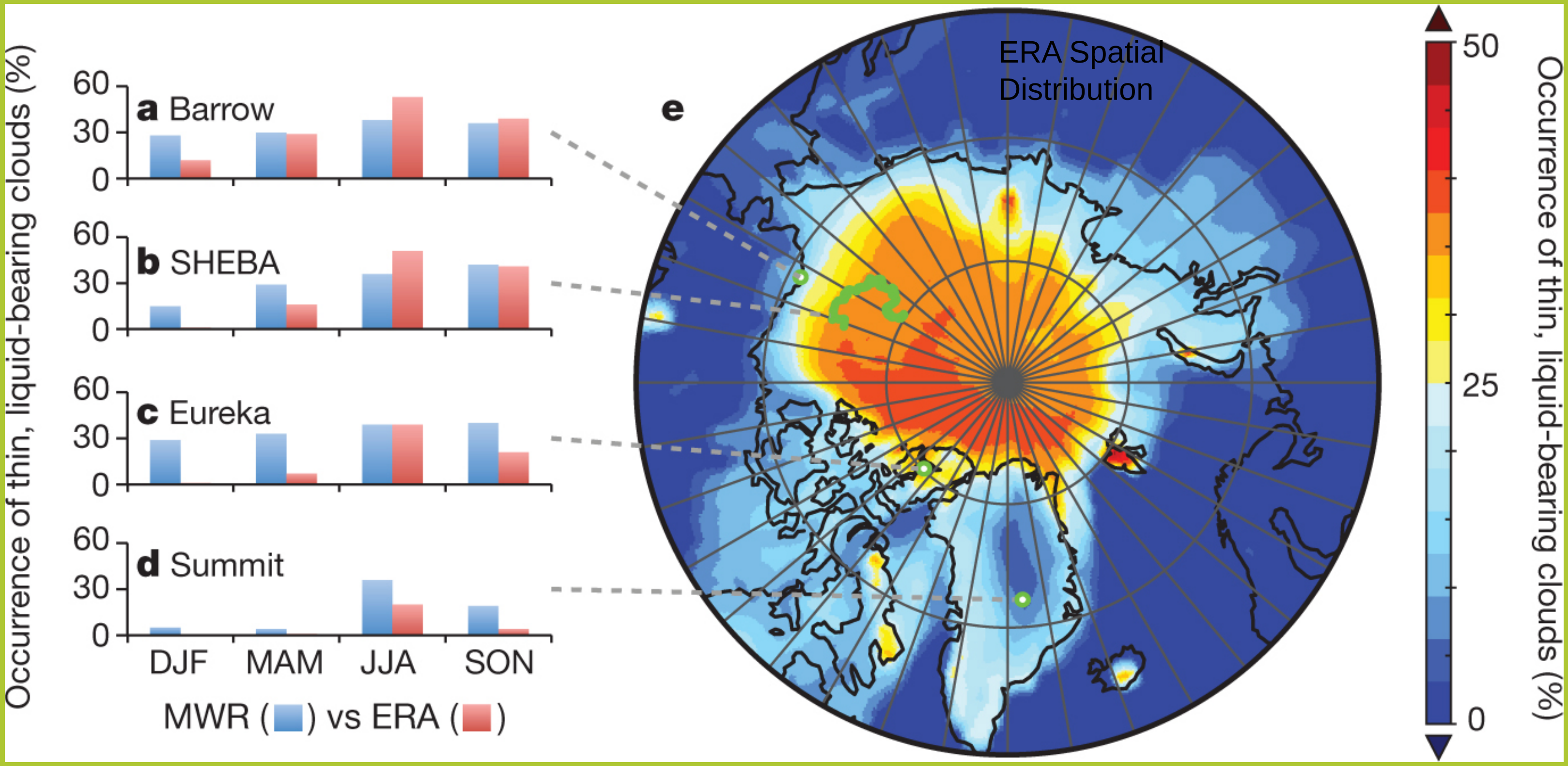


SHEBA Observations



"Thin, liquid clouds" in Observations and Reanalyses (Models)

For the purpose of this plot, '**thin, liquid-bearing' clouds are defined as** clouds in the range of **$10\ g\ m^{-2} < LWP < 60\ g\ m^{-2}$,** corresponding to the range of maximum enhanced cloud radiative forcing at the surface. **a**–**d**, Comparisons of ground-based observed (blue, microwave radiometer (MWR)) and ERA-Interim simulated (red, ERA) frequencies of occurrence of these clouds for four Arctic observation sites for all seasons; **a**, Barrow, Alaska; **b**, Surface Heat Budget of the Arctic Ocean (SHEBA) experiment **c**, Eureka, Nunavut; and **d**, Summit, Greenland. **e**, Circumpolar map of the frequency of occurrence of these clouds from 32 yr of ERA reanalysis (1979–2011). The plot in **e** is conditionally sampled to only include cases with solar zenith angle lower than 80° and a surface albedo higher than 0.5.



Frequency of thin, LW clouds too low for ERA-I in spring/autumn and much too low in winter.

R Bennartz *et al. Nature* **496**, 83-86 (2013) doi:10.1038/nature12002

Single-column modeling of Sc clouds – effects of CCN (Birch et al 2012)

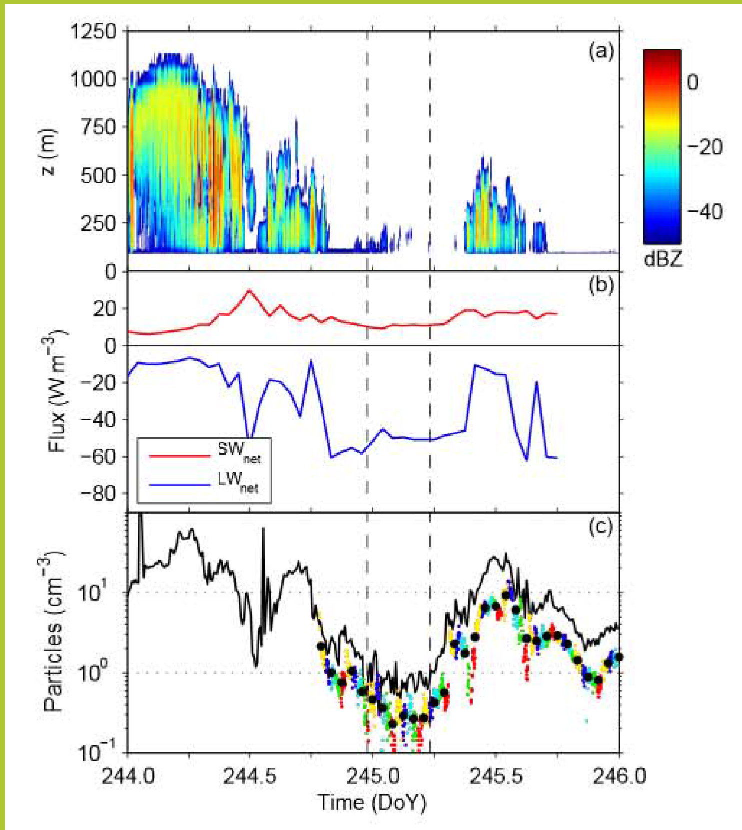


Fig. 8. Cloud and aerosol observations from the 5th regime **(a)** radar reflectivity, **(b)** observed net shortwave and longwave radiative fluxes and **(c)** accumulation mode particle (60 nm < diameter < 800 nm) concentration from the DMPS (black line) and mean CCN concentration (black dots), computed from measurements made at a range of supersaturations (coloured dots, red 0.11 %, green 0.16 %, cyan 0.21 %, blue 0.42 % and yellow 0.73 %). The vertical dashed lines show the times of the two radiosondes used in the SCM runs in Figs. 9–11.

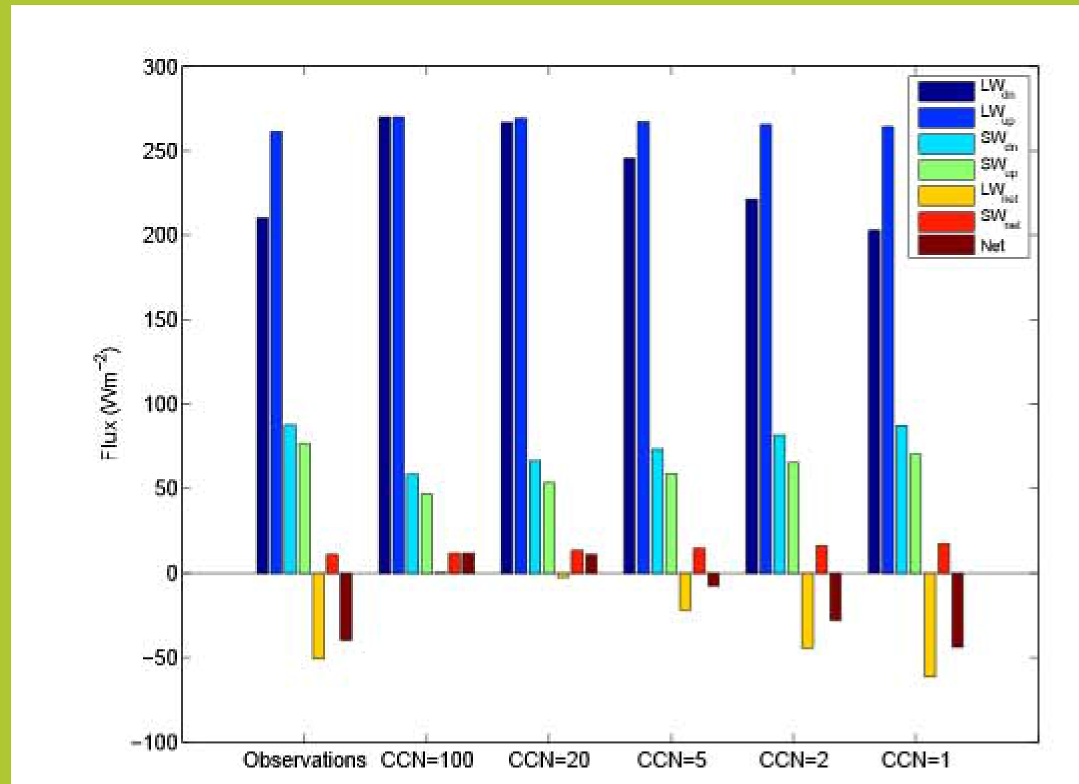
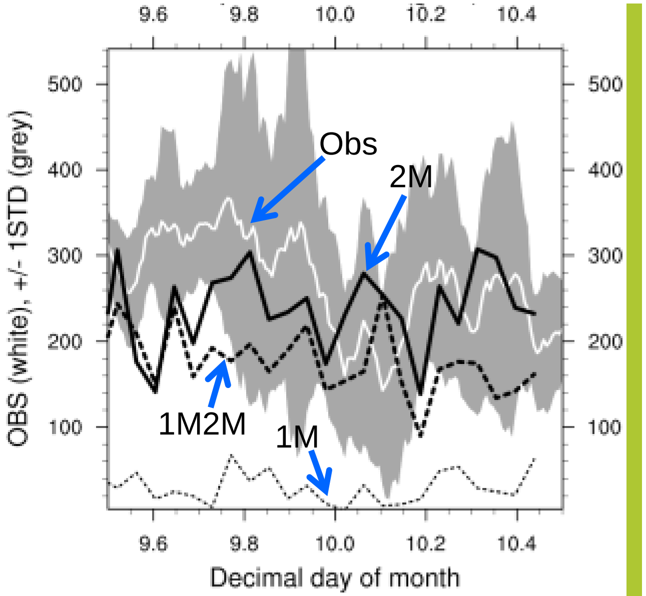


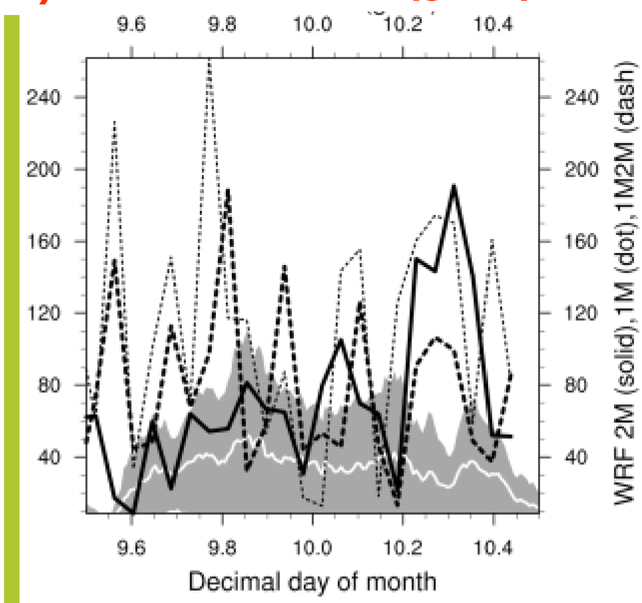
Fig. 10. Mean radiative flux observations between 05:00 and 06:00 UTC, DoY 245 and radiative flux diagnostics at $t + 6$ h from the SCM run initialised at 23:30 UTC, DoY 244.

Birch et al (2012)
Single column model
Only when CCN=1-2 cm^{-3} (as observed) was model able to produce observed LW_{net} and surface net radiative flux.
Implication: CCN conc. modulates LWP, and hence LW_d

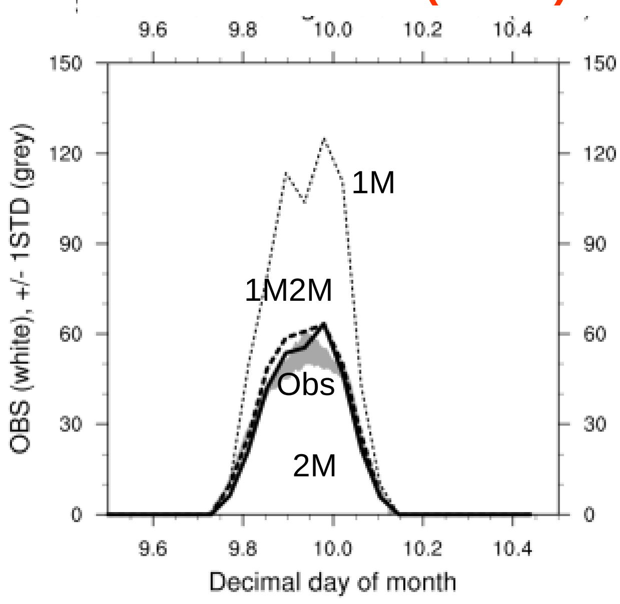
Cloud Liquid Water Path (g m^{-2})



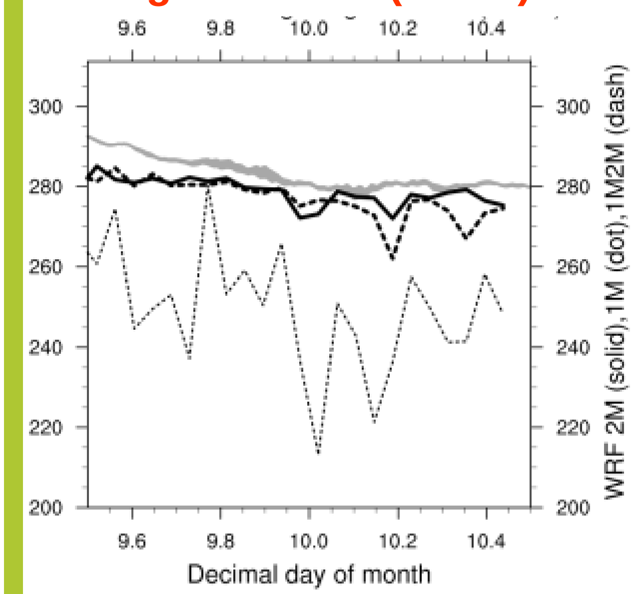
Ice Water Path (g m^{-2})



Shortwave Flux (W m^{-2})



Longwave Flux (W m^{-2})



Solomon et al 2010

Arctic stratocumulus clouds Near Barrow MPACE, Oct. 2004

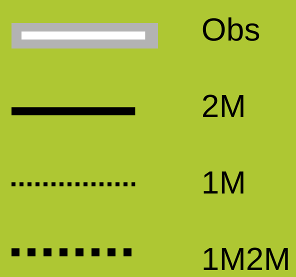
Single moment microphysics (1M):
prognostic equation for mass concentration (λ varies, N_0 fixed)

Double moment microphysics (2M):
prognostic equation for mass and number concentration. (λ varies, N_0 varies)

Morrison and Pinto 2006

Microphysics Results

1) LWP much improved with 2M vs 1M – maintain supercooled liquid water
2) IWP better with 2M, but still high



Radiative Fluxes Results

1) SW_d & LW_d much improved with 2M vs 1M

Summary of Arctic Clouds

I. Observations

A) Clouds are a key component of the Arctic environmental system

B) Primarily 2 types of clouds have major impacts – Sc (low, shallow) and Ns (deep, precipitating)

1) low-level (Sc) clouds occur 40-55% of time; deeper (mid-level) clouds less frequent

C) Formation mechanisms

1) Ns – dynamical (frontal) forcing, especially aloft (occluded systems); active formation vs advection from lower latitudes uncertain

2) Sc – longwave atmospheric (cloud-top) radiative cooling
   - produces intermittent vertical mixing to surface, and impacts BL structure

3) moisture transport from lower latitudes likely important for both, though transport from local surface also occurs for Sc

D) Impacts on surface

1) radiative forcing on surface
   - both cloud types have significant impacts, but some (unknown) differences may exist
   - cloud phase (presence of LW) key aspect for impact on surface energy budget
   - sensitivity strong for the low values of LWP often encountered

2) precipitation
   - albedo change; important for surface energy budget balance and triggering melt/freeze transitions
   - thermal conductivity; important for sea ice/permafrost growth & melt

Summary of Arctic Clouds - cont.

II. Modelling

Issues in Quantitatively Modeling Key Arctic Cloud Processes & Feedbacks

1) production of CLW very inconsistent; often far underdone for supercooled (mixed-phase) conditions; double-moment microphysics enhance supercooled liquid in Sc clouds, but may have unwanted and not understood feedbacks
2) formation of BL clouds (and impact on BL structure and mixing) may depend on model presence of moisture inversion and parameterization of the shallow cloud-top turbulence (entrainment)
3) unknown validation of deeper synoptic/mesoscale clouds and precipitation in Arctic
   - lack of observations
   - OK because of good SLP validation?
4) coupling between aerosols (CCN and IN) for cloud formation inadequate in most models (often constant concentrations throughout domain) – low CCN/IN concentrations lead to greater sensitivity
5) radiative errors from poor cloud representation interacting with other inadequate representations (e.g., snow/sea-ice representation) produce inaccurate process relationships and frequently compensating errors in surface energy budget
6) poor representation of clouds (and sea-ice environment) in reanalyses important because of their frequent use for forcing regional atmospheric, cryospheric, and ocean models, and because of their use in climate diagnostics studies