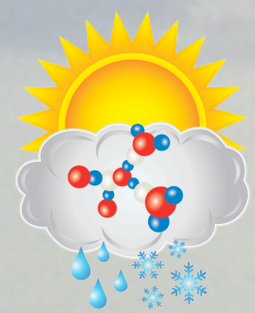
Thoughts on Cloud Phase in Stratiform Clouds

Gijs de Boer

Including contributions from:

A. Del Genio, J. English, A. Fridlind, A. Gettelman, S. Ghan, J. Harrington, J. Kay, S. Klein, H. Morrison, M. Ovchinnikov, P. Rasch, M. Shupe, H. Wang

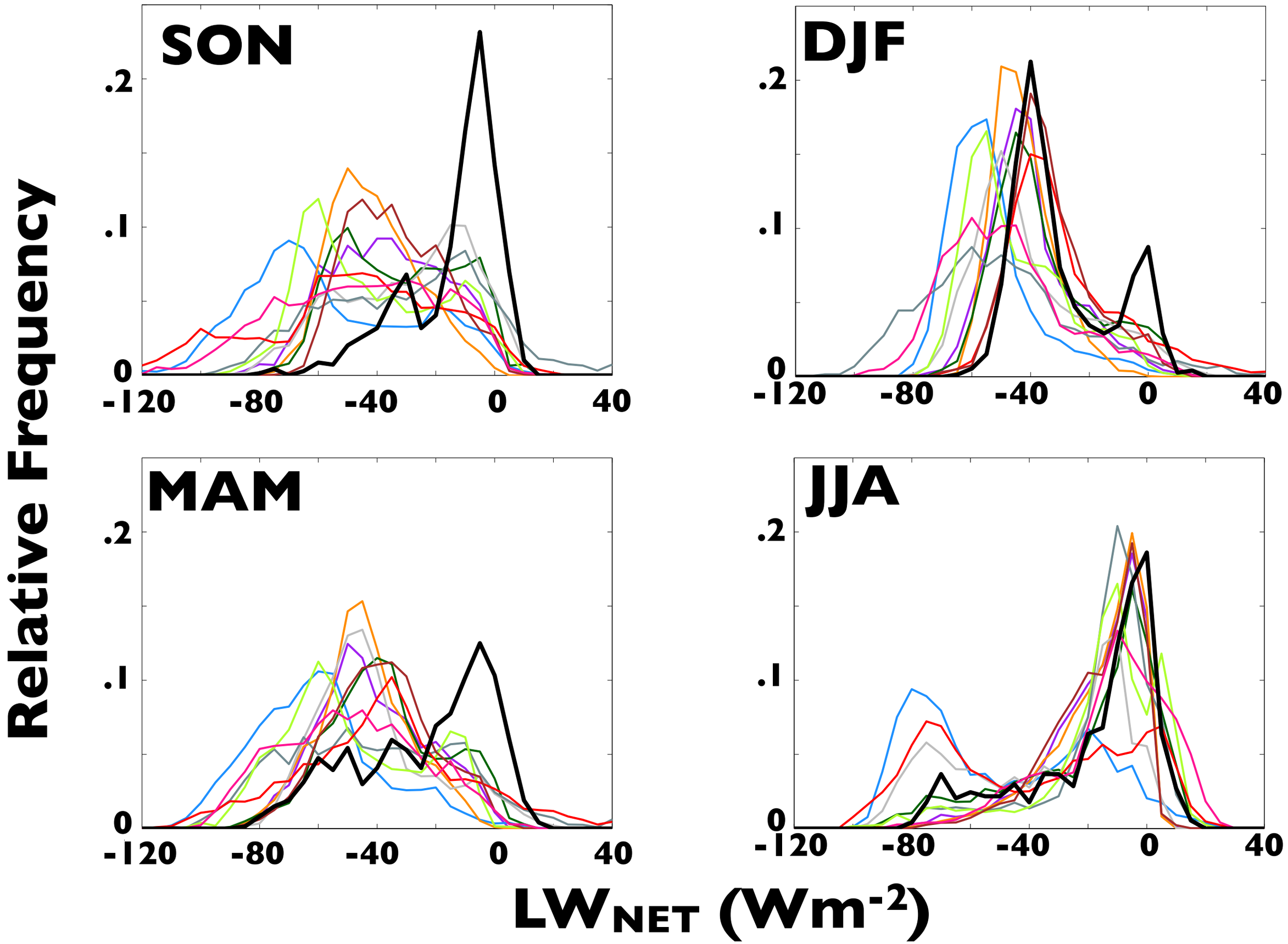
U.S. DEPARTMENT OF ENERGY



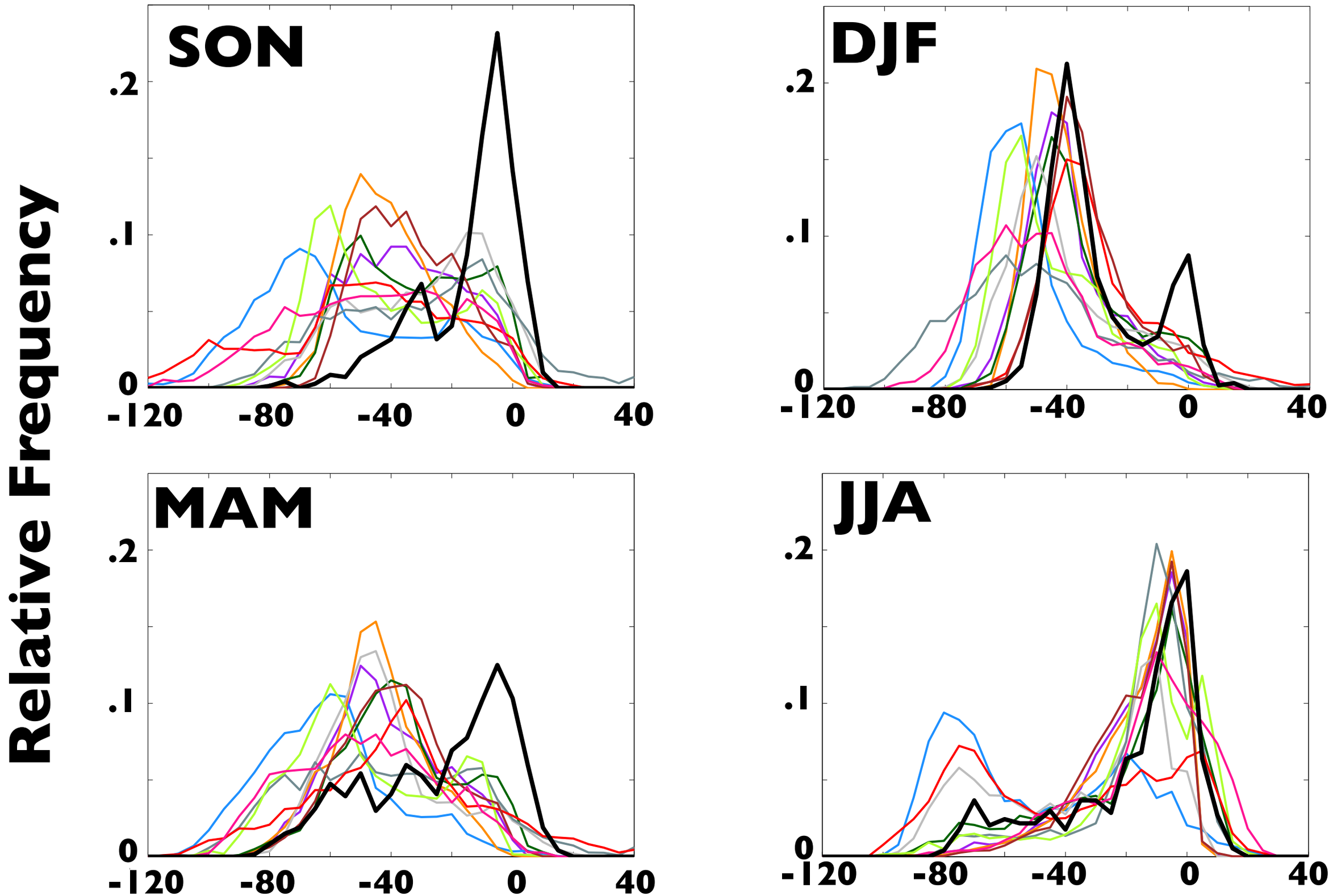
ASR
Atmospheric System Research

ASR Fall Working Groups Meeting, 28 October-2 November, 2012

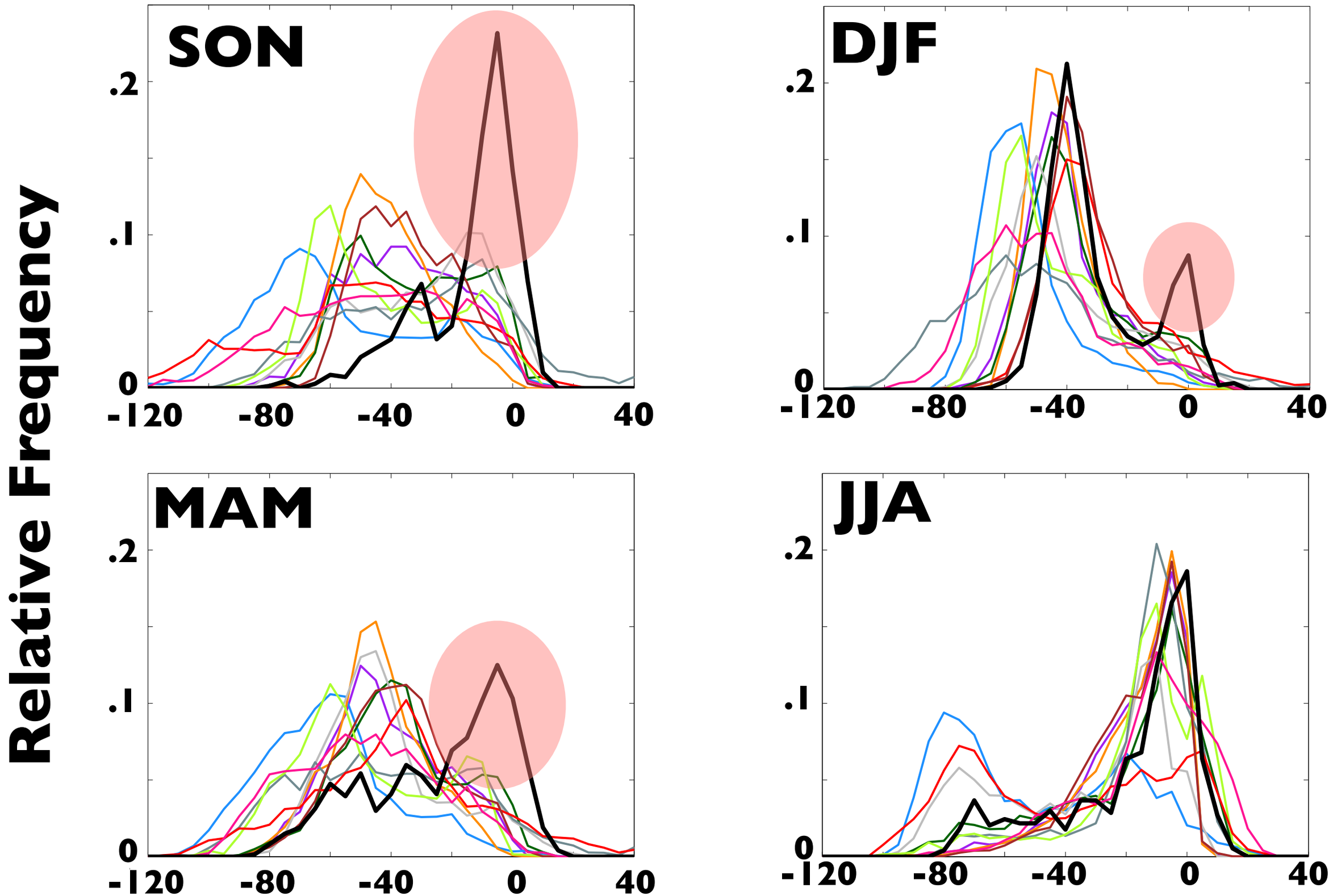
Climate Model Performance



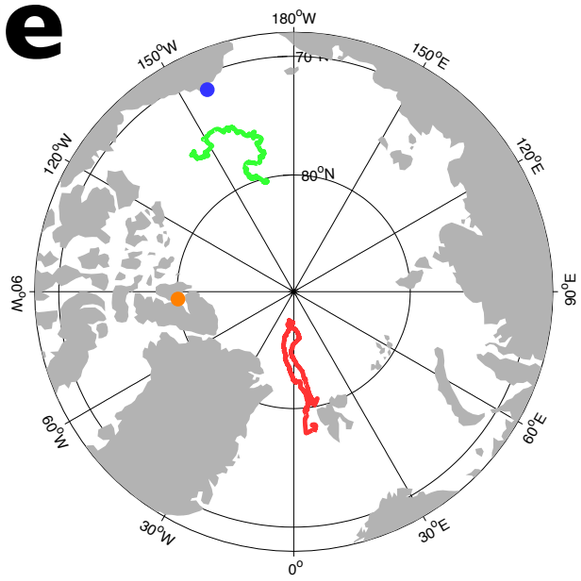
Climate Model Performance



Climate Model Performance



Climate Model Performance

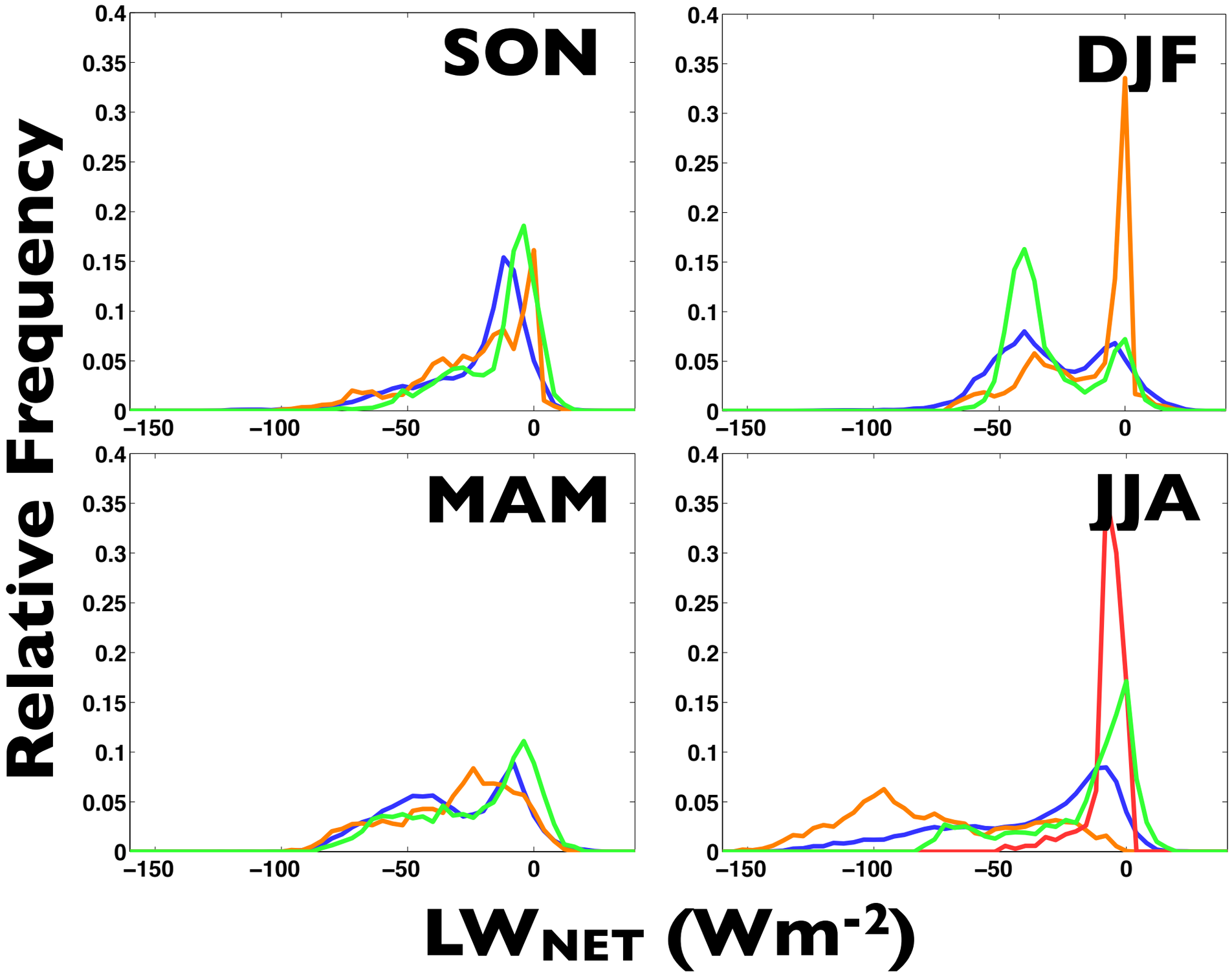


Barrow
01/2001-01/2010

Eureka
09/2008-05/2010

ASCOS
08/2008

SHEBA
10/1997-09/1998



Climate Model Performance

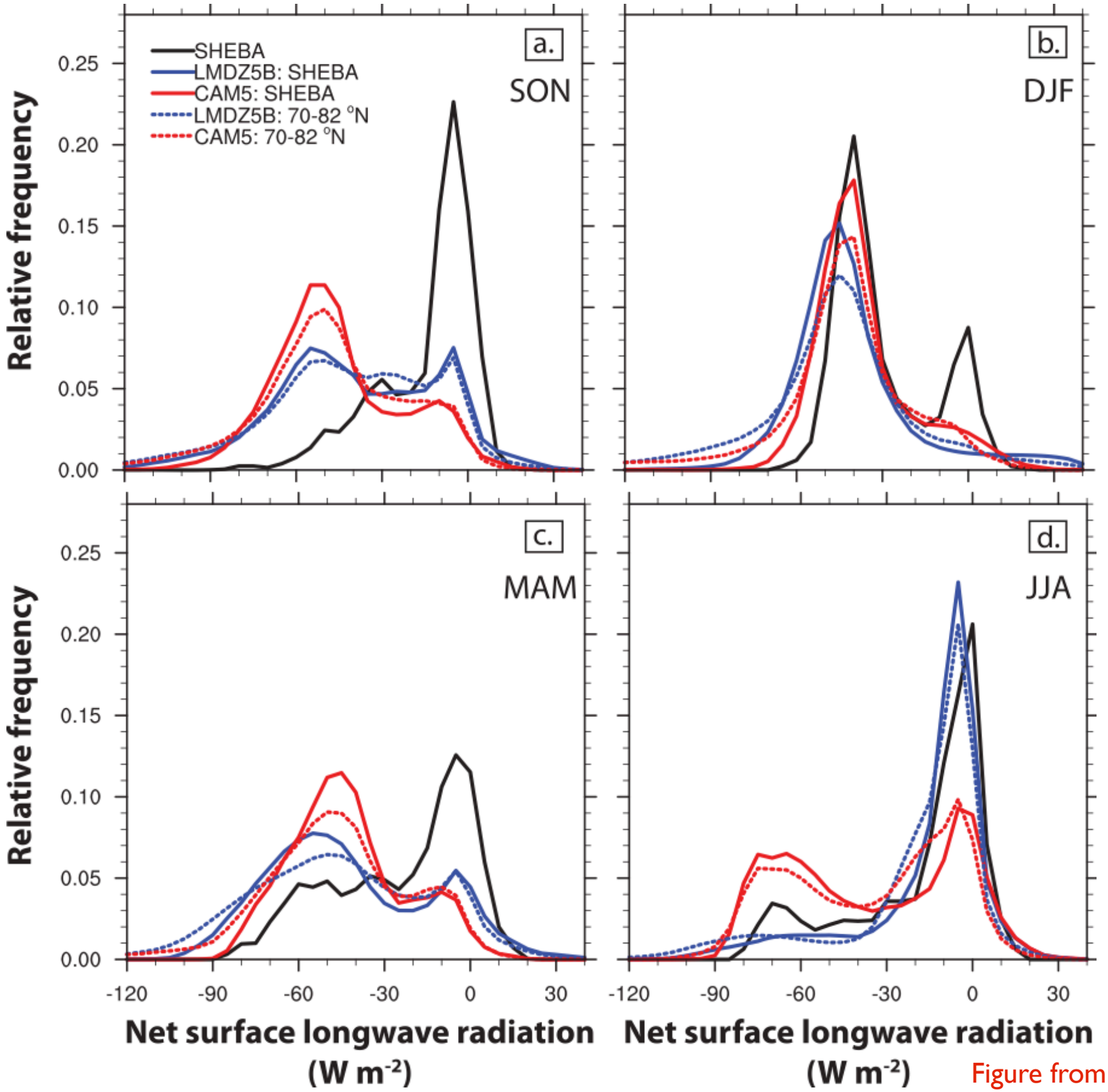


Figure from Cesana et al., (2012)

Climate Model Performance

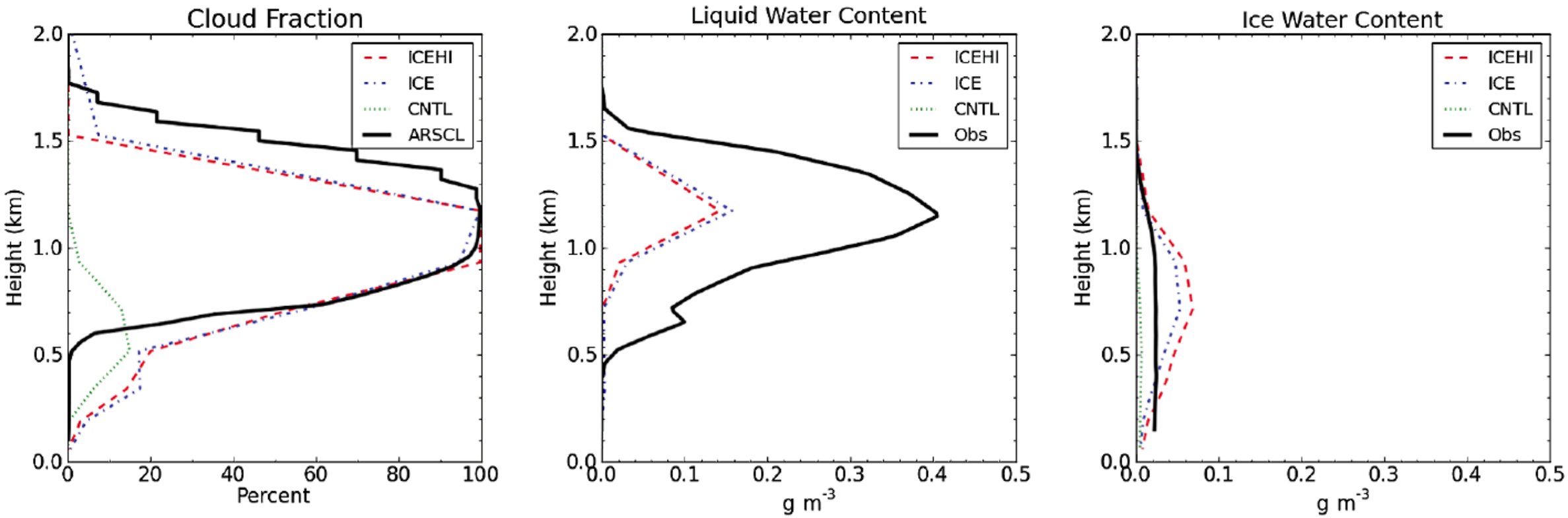


Figure 2. Height-profile of quantities averaged over the period 1200 UTC 9 October to 1200 UTC 10 October during MPACE. (left) Cloud fraction (%). (middle) Liquid water content. (right) Ice water content. Observations in black. Cloud fraction observations are from Active Remotely Sensed Cloud Locations (ARSCL) [*Clothiaux et al.*, 2000]; liquid and ice water content are from *Shupe et al.* [2008]. Simulations for CNTL (green dash), ICE (blue dash), and ICEHI (red) shown.

Figure from Gettelman et al., (2010)

Relevance of Phase

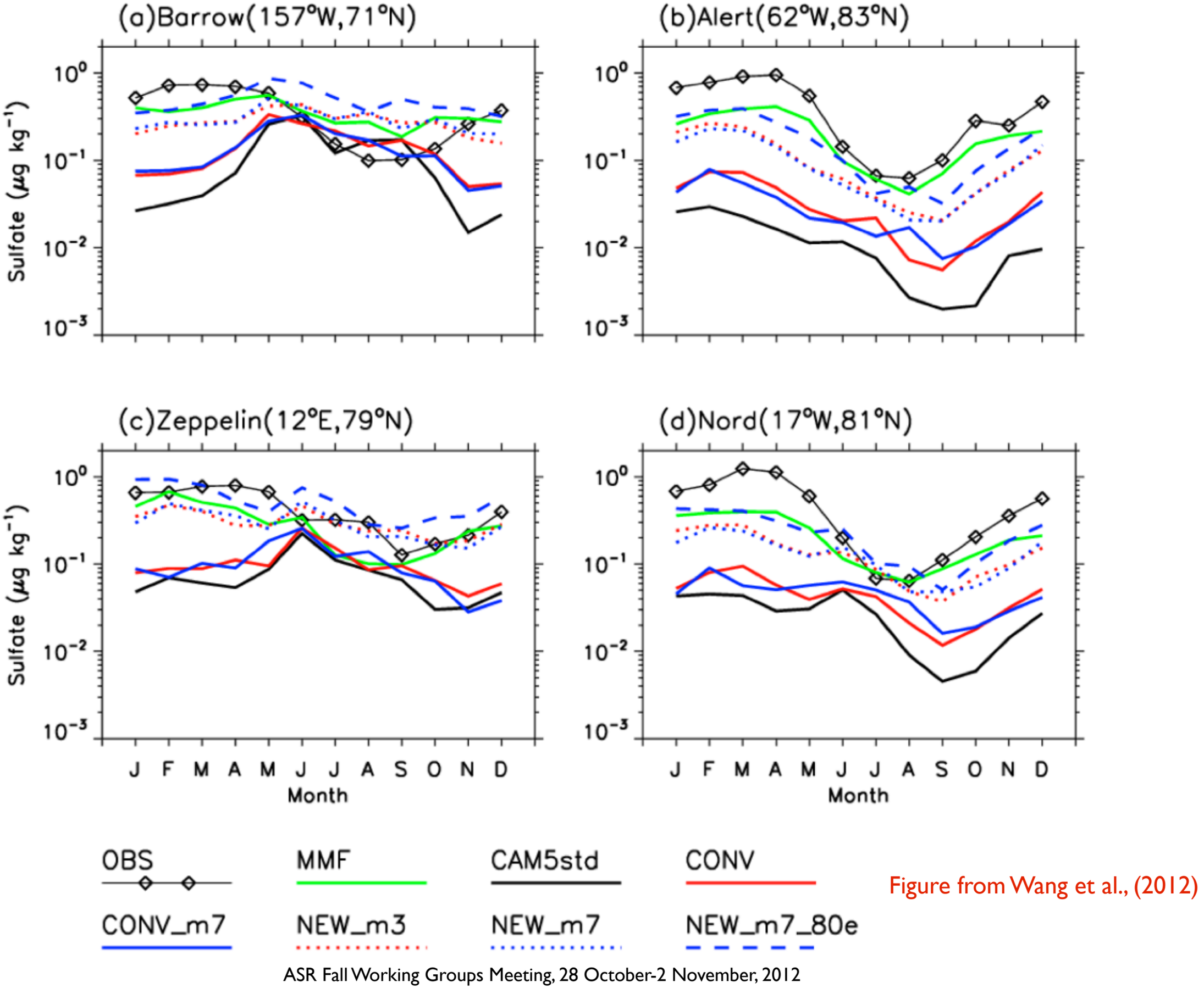
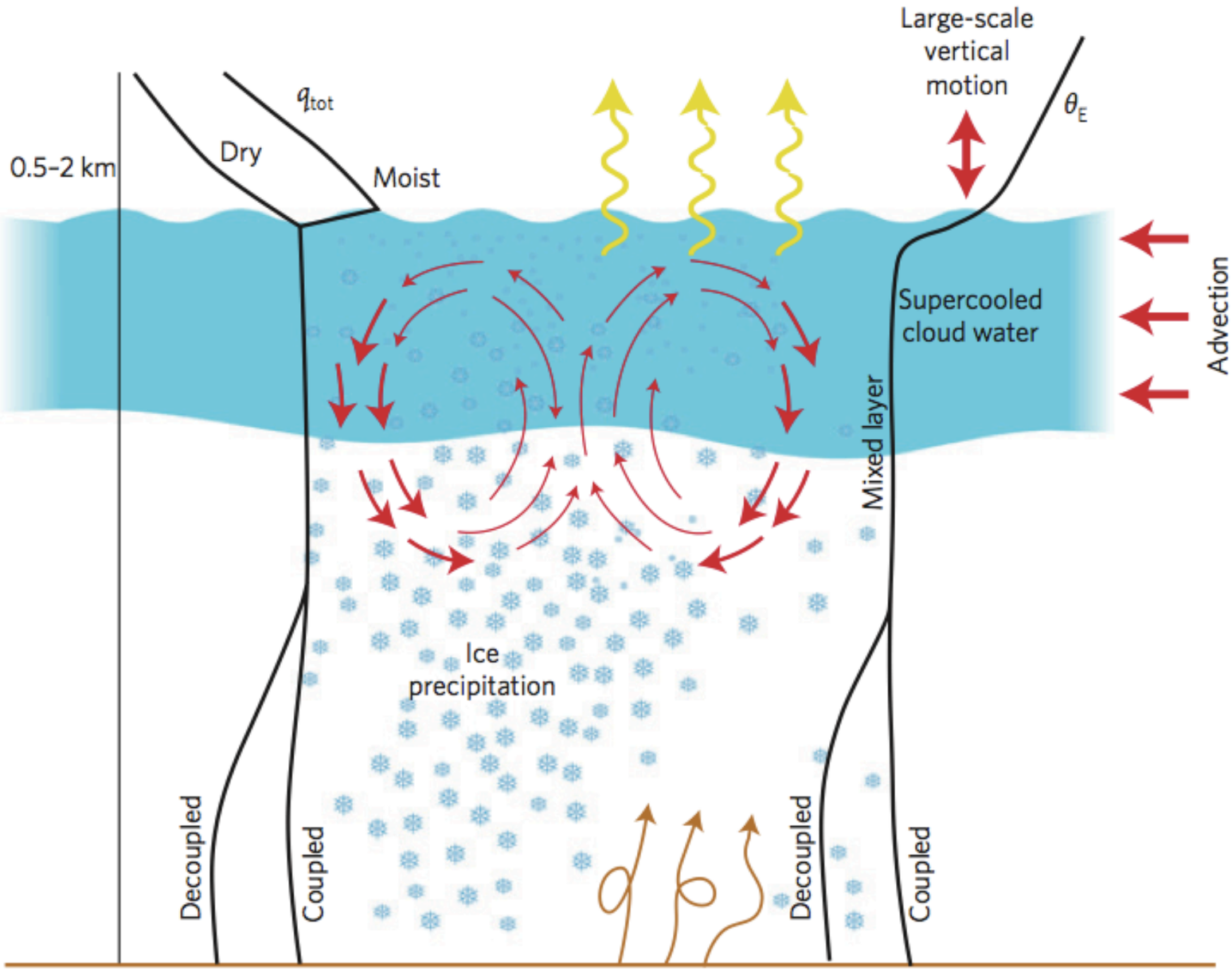


Figure from Wang et al., (2012)

A Complex Picture



Radiative Cooling
- Drives buoyant production of turbulence
- Forces direct condensation within inversion layer
- Requires minimum amount of cloud liquid water

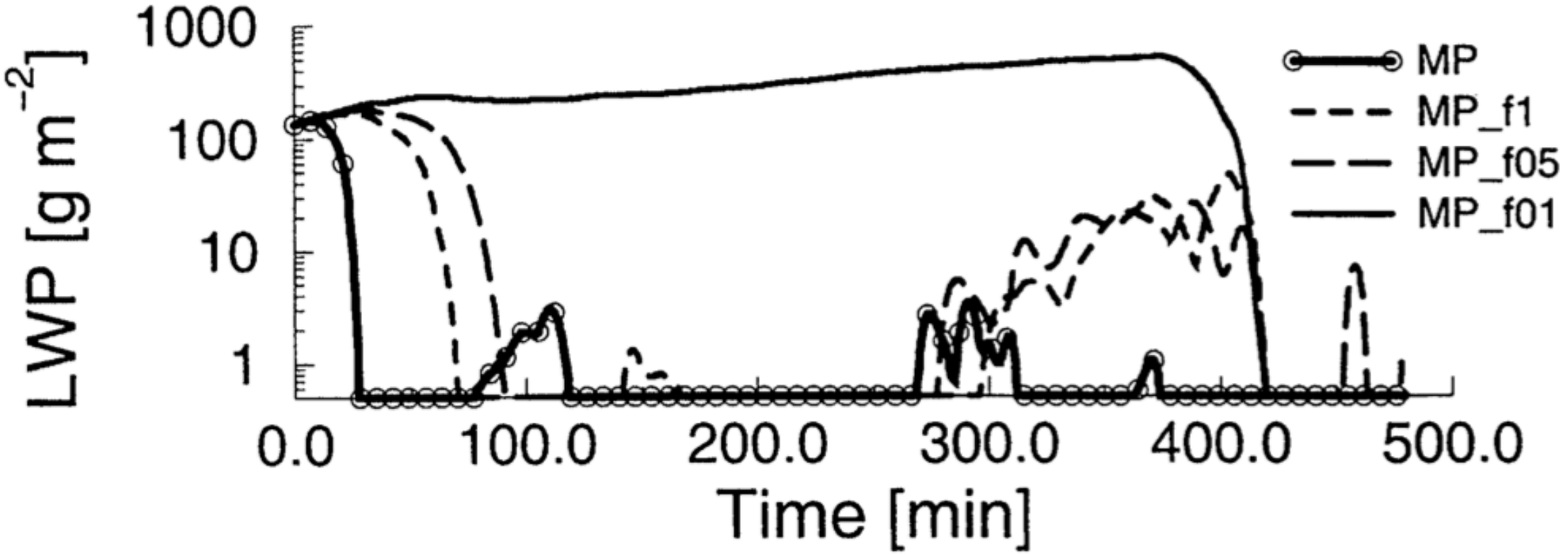
Microphysics
- Liquid forms in updrafts and sometimes within the inversion layer
- Ice nucleates in cloud
- Rapid ice growth promotes sedimentation from cloud

Dynamics
- Cloud-forced turbulent mixed layer with strong narrow downdrafts, weak broad updrafts, and q_{tot} and θ_E nearly constant with height
- Small-scale, weak turbulence in cloudy inversion layer
- Large-scale advection of water vapour important

Surface Layer
- Turbulence and q contributions can be weak or strong
- Sink of atmospheric moisture due to ice precipitation
- Surface type (ocean, ice, land) influences interaction with cloud

Figure from Morrison et al. (2012)

High Resolution Modeling



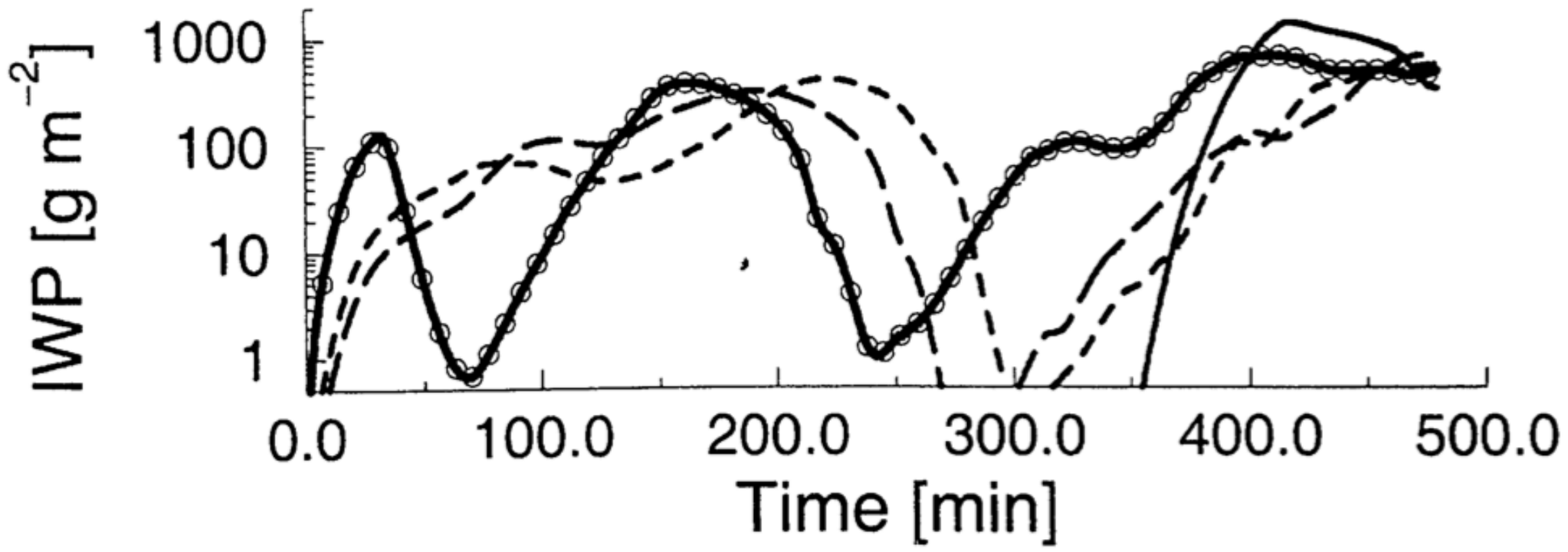


Figure from Harrington and Olsson (2001)

High Resolution Modeling

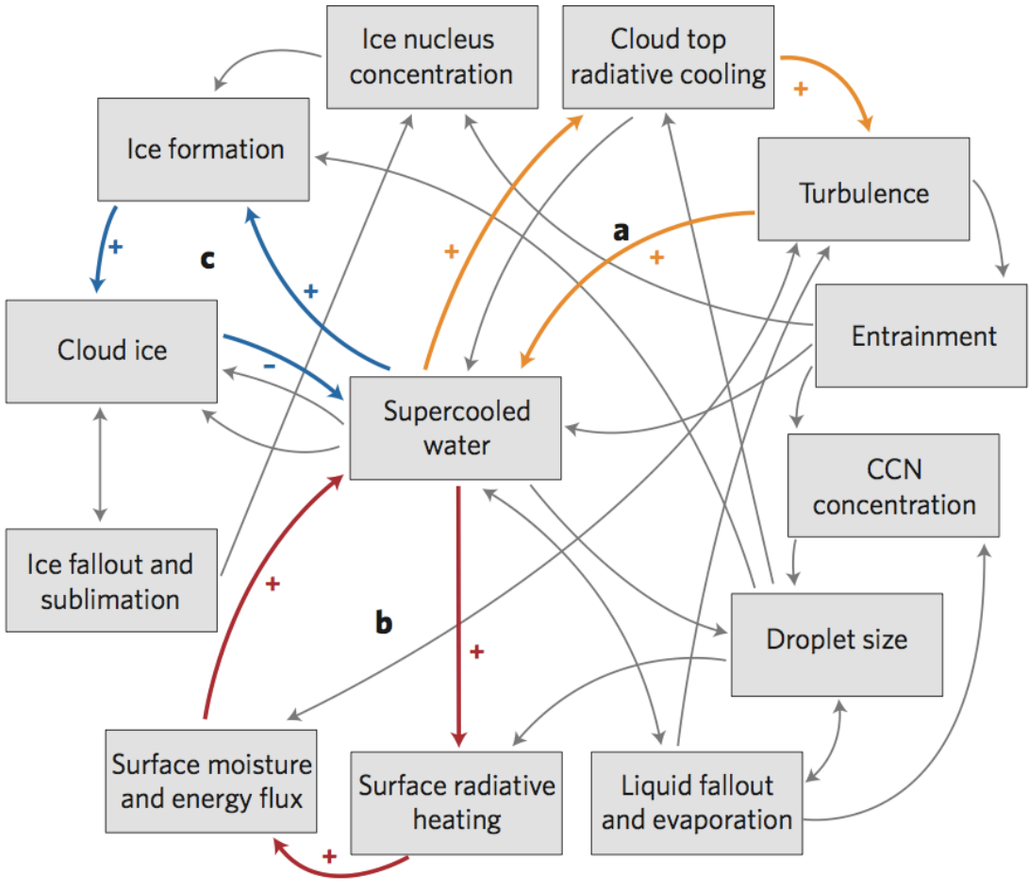


Figure from Morrison et al. (2012)

High Resolution Modeling

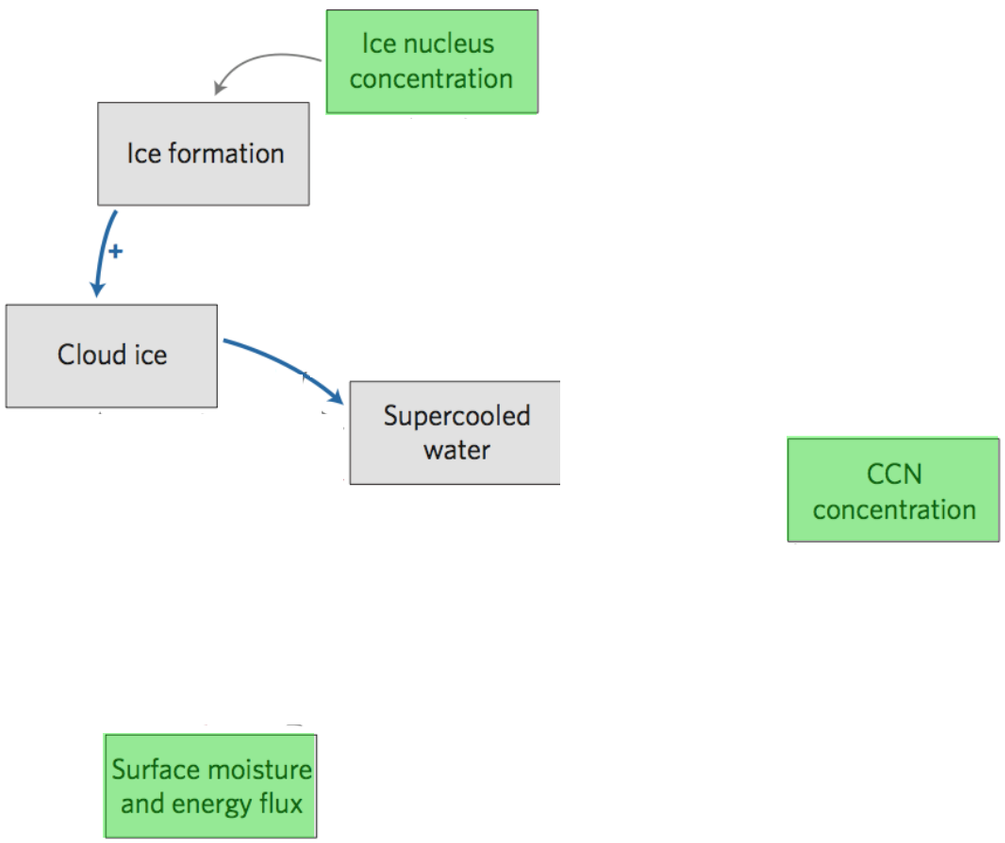


Figure from Morrison et al. (2012)

High Resolution Modeling

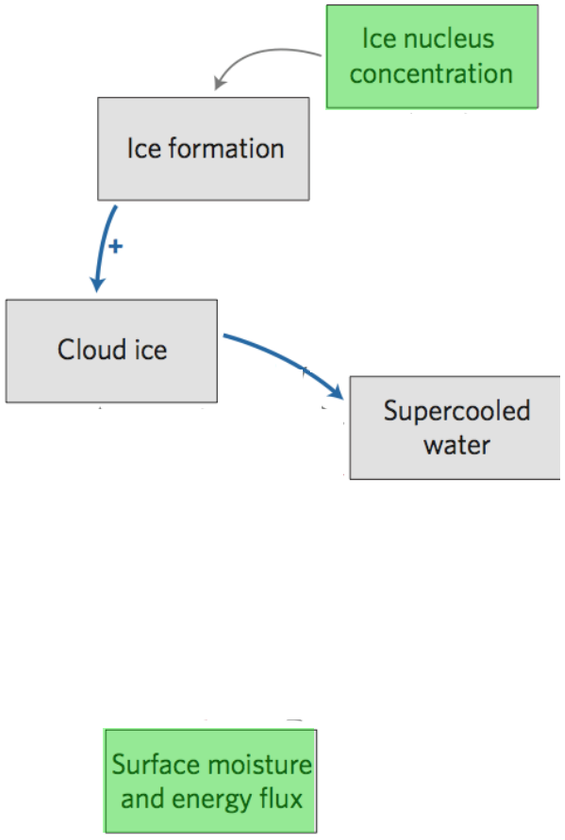
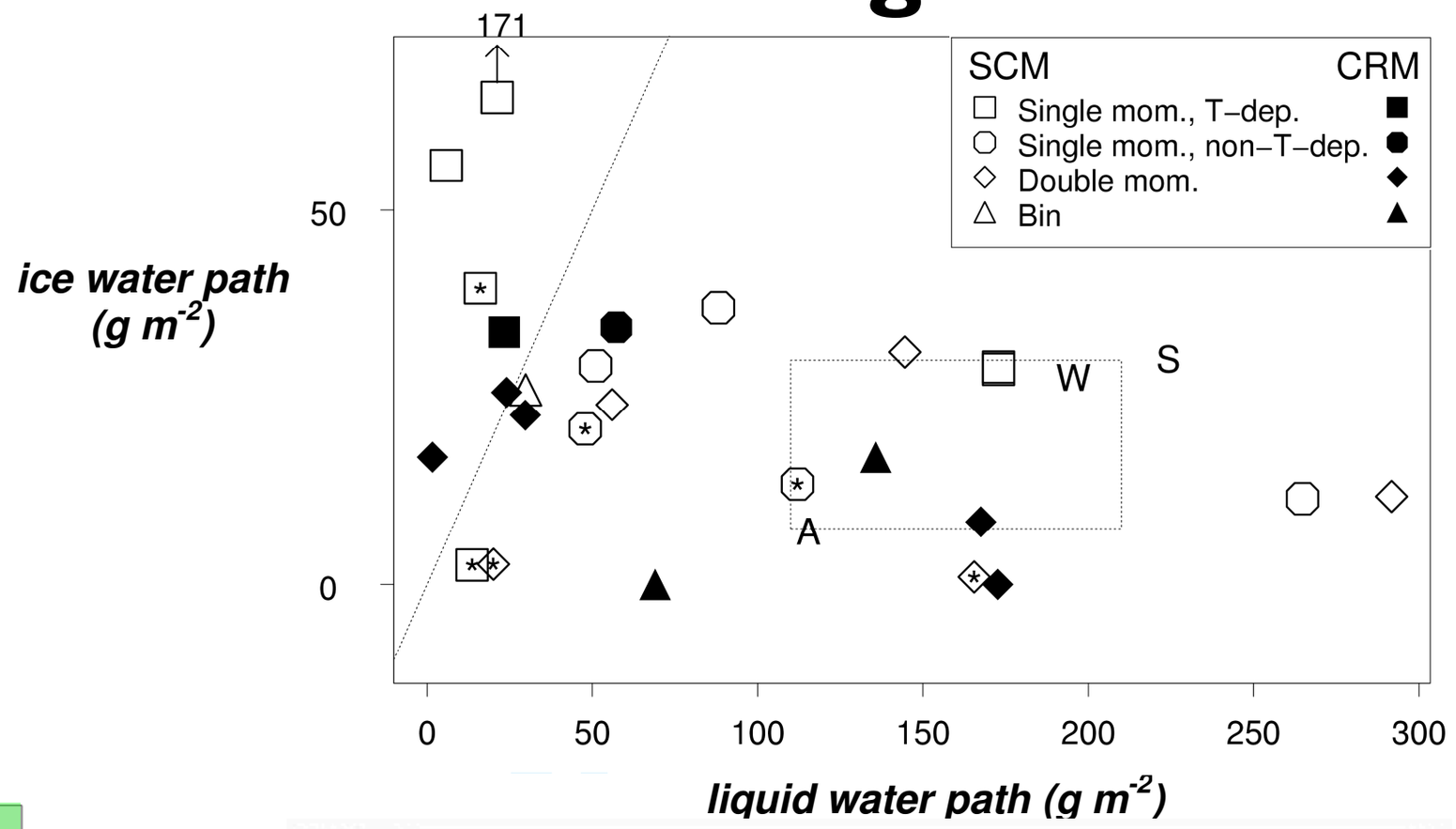


Figure from Morrison et al. (2012)



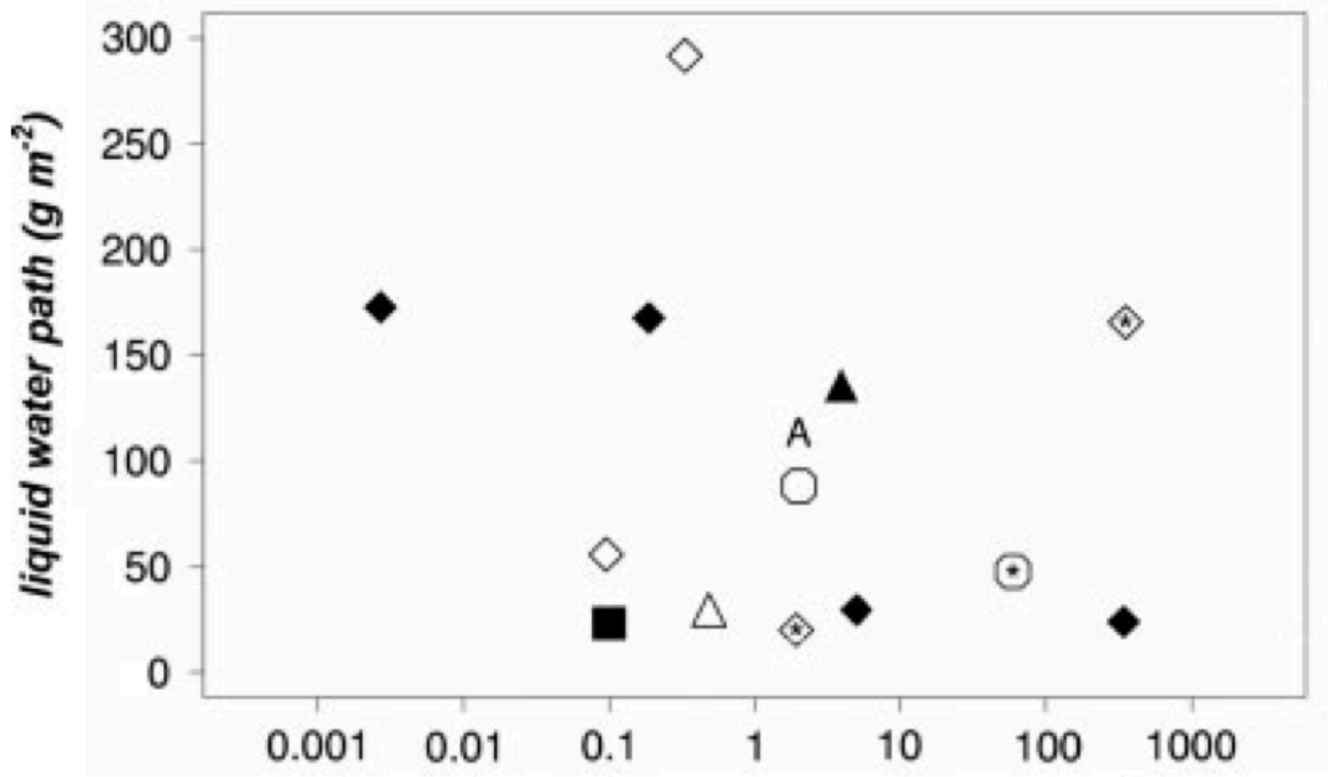
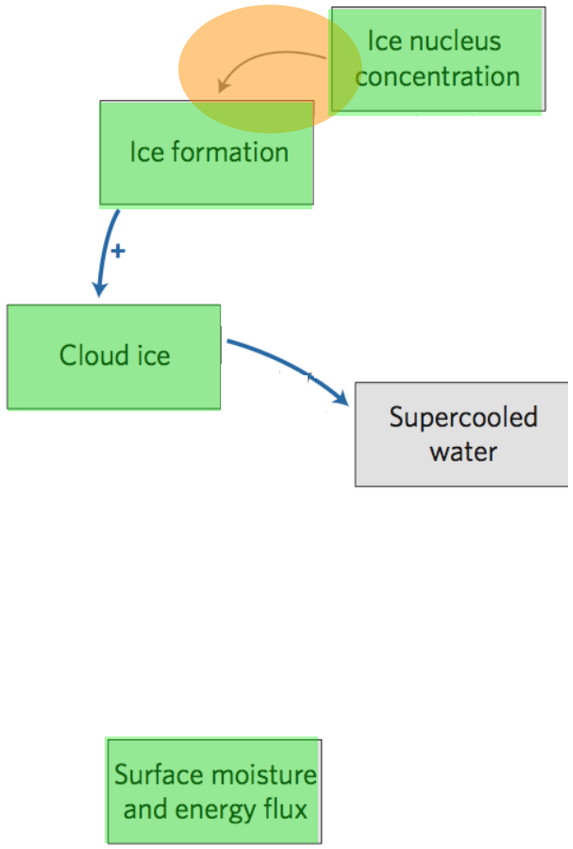


Figure from Klein et al. (2009)

High Resolution Modeling



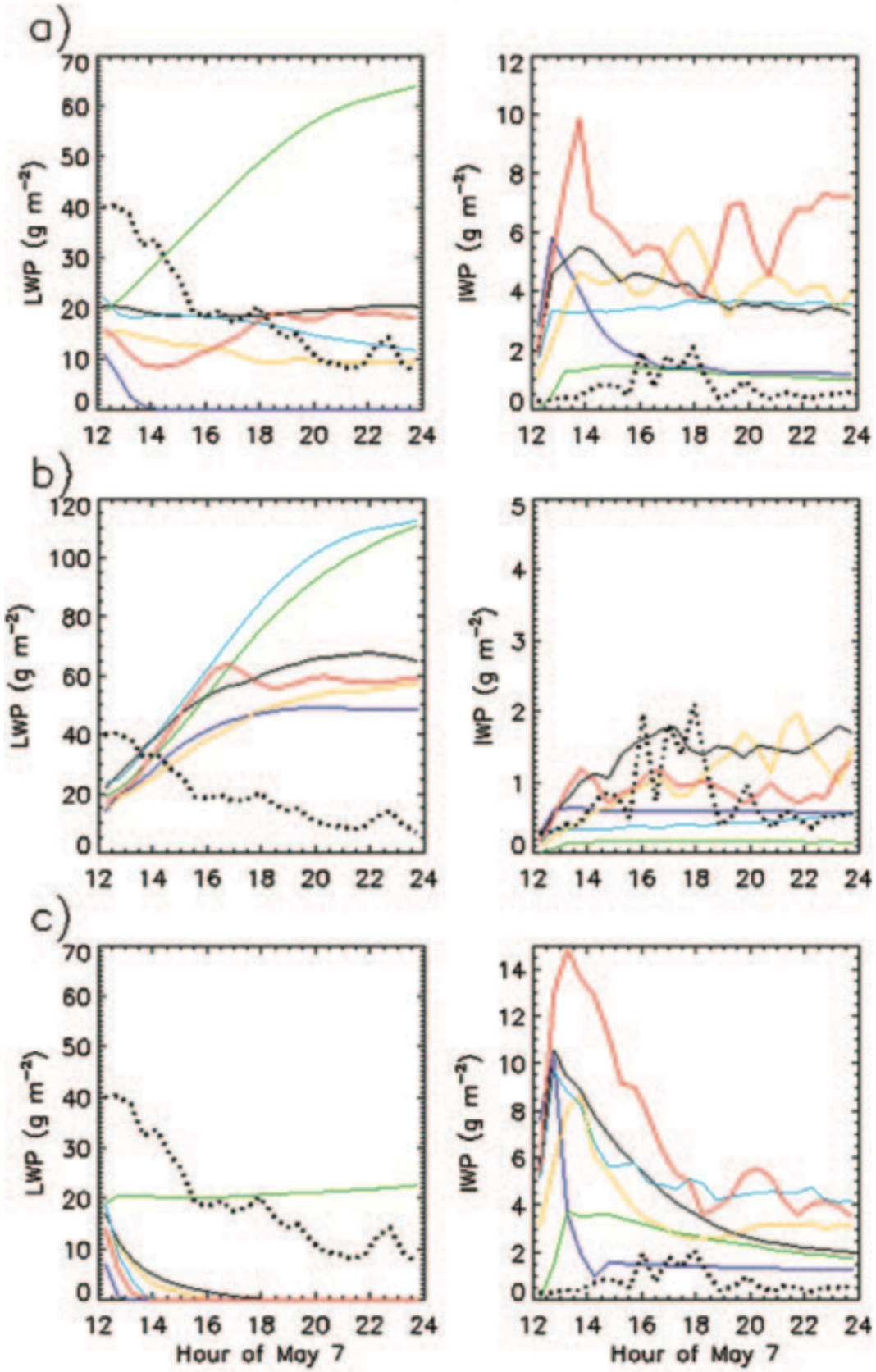
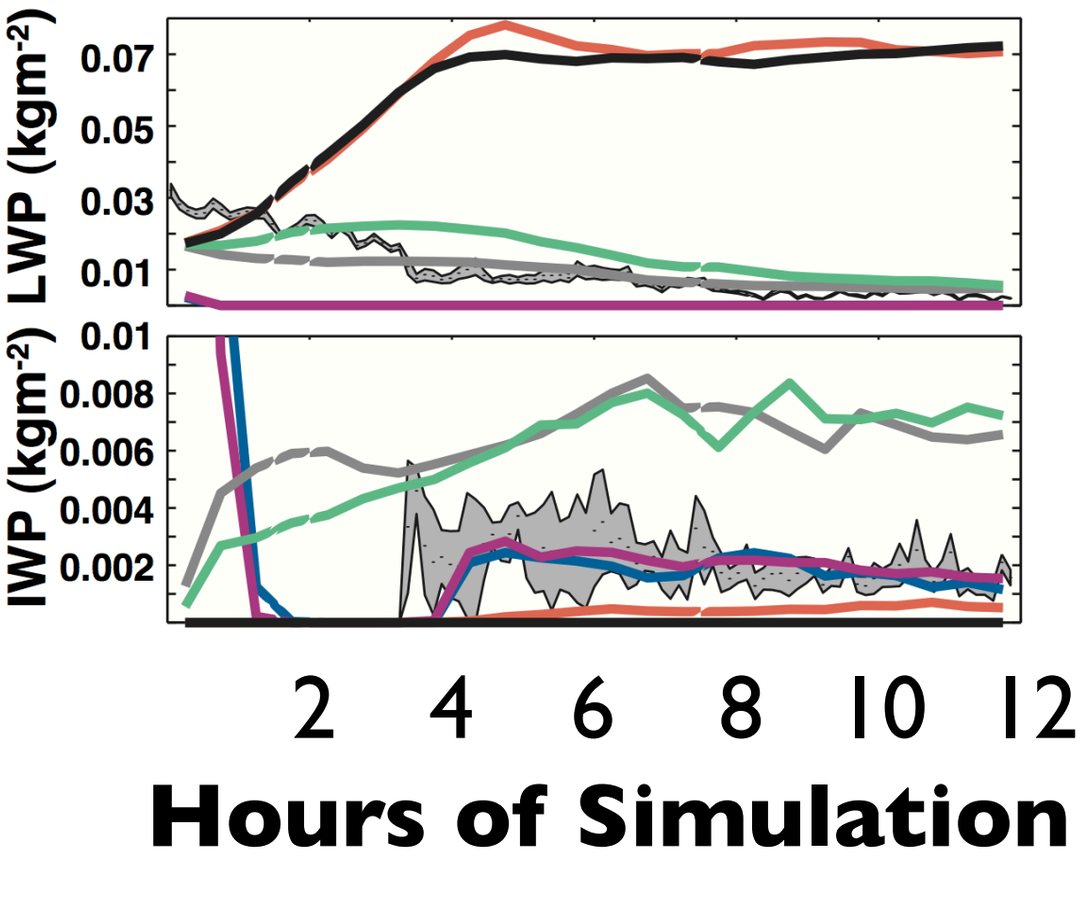


Figure from Morrison et al. (2011)

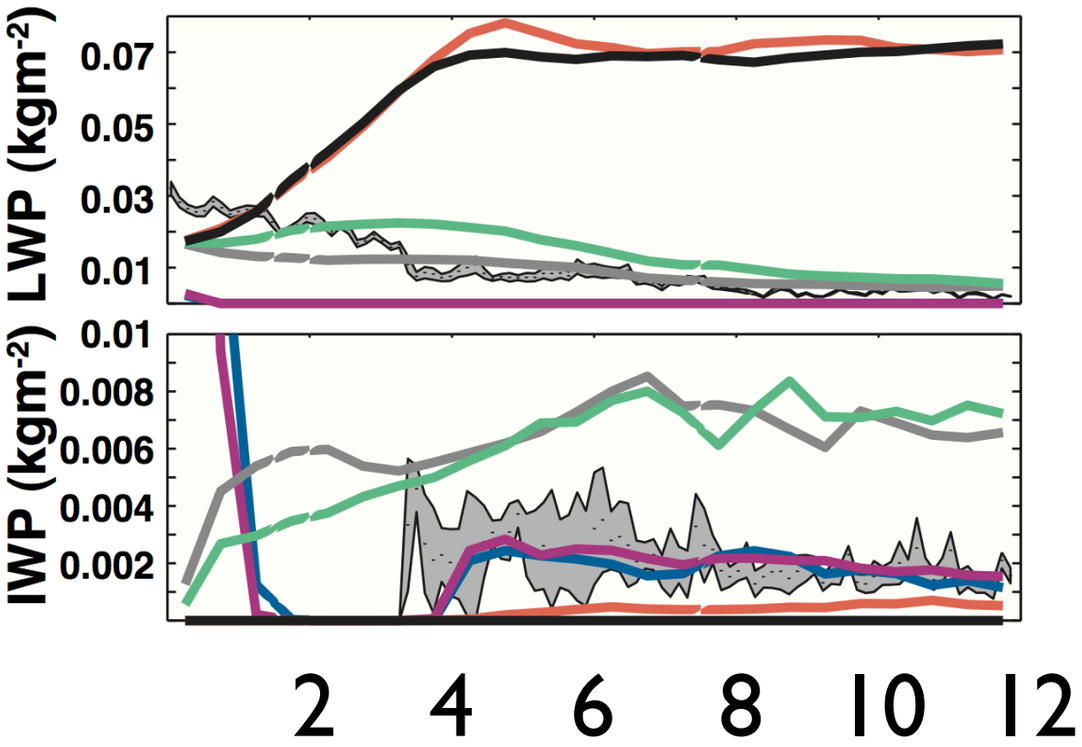
High Resolution Modeling

Figure from de Boer et al. (2012b)



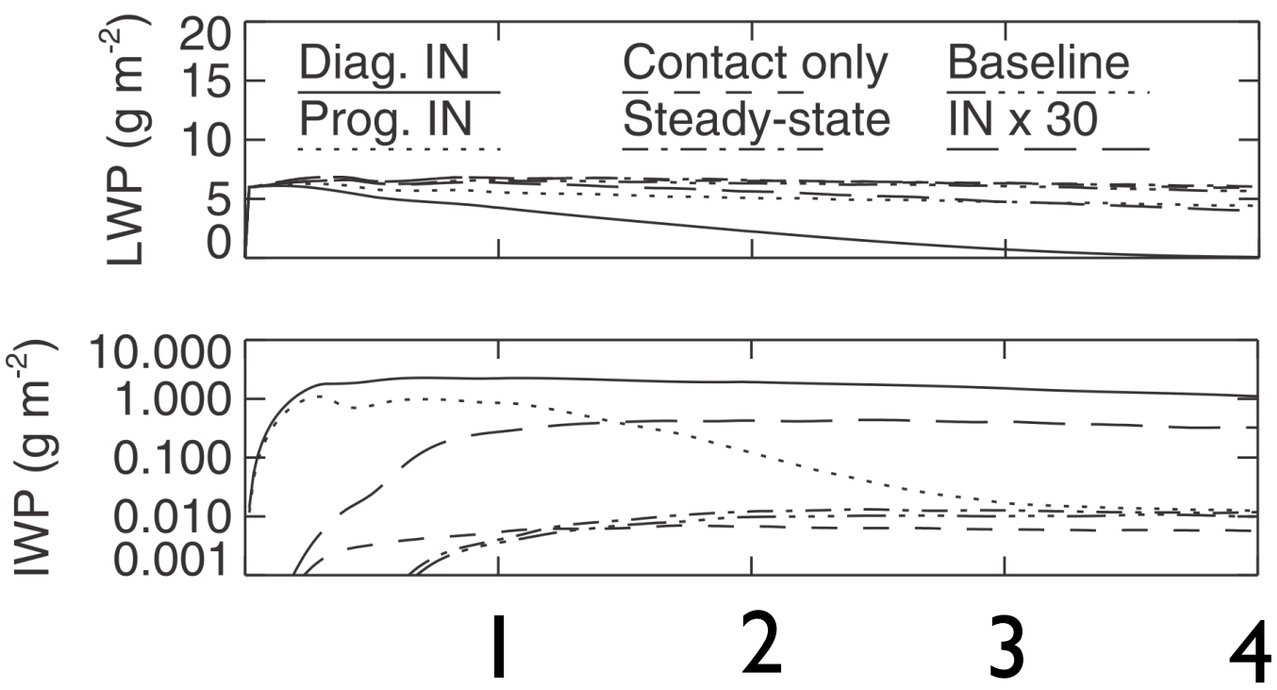
High Resolution Modeling

Figure from de Boer et al. (2012b)



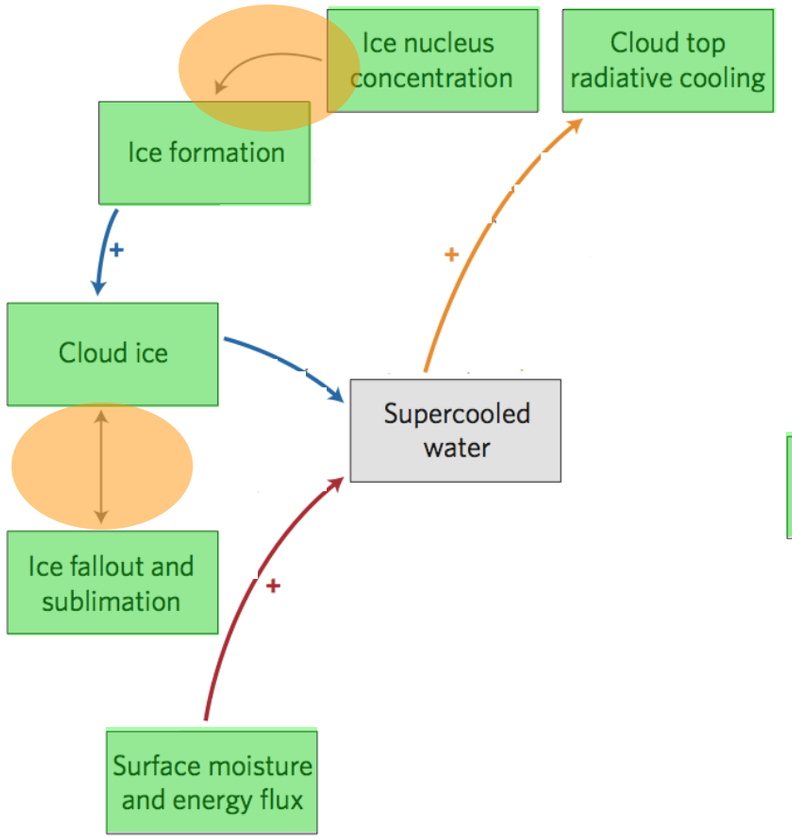
Hours of Simulation

Figure from Fridlind et al. (2012)



Hours of Simulation

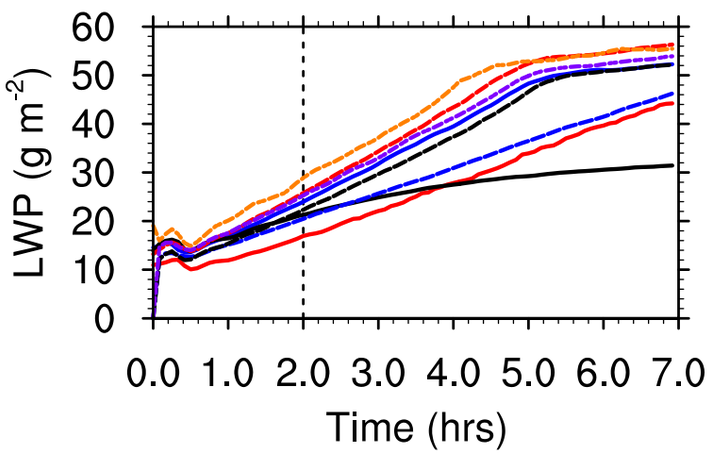
High Resolution Modeling

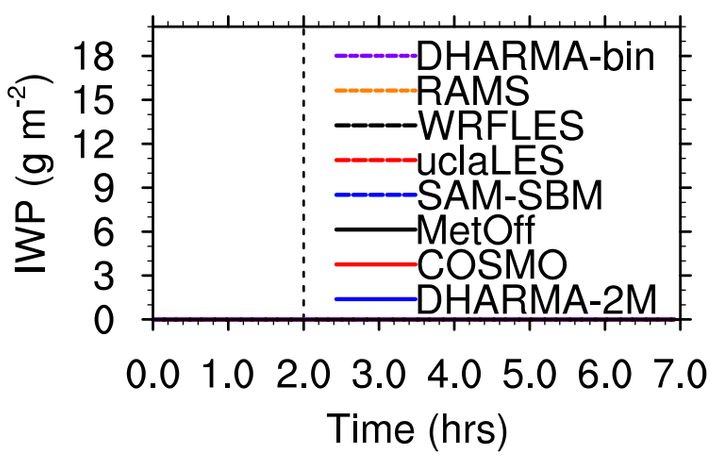


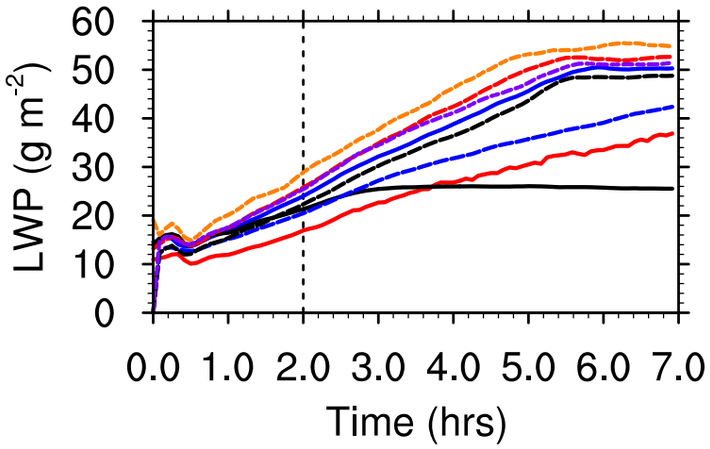
CCN concentration

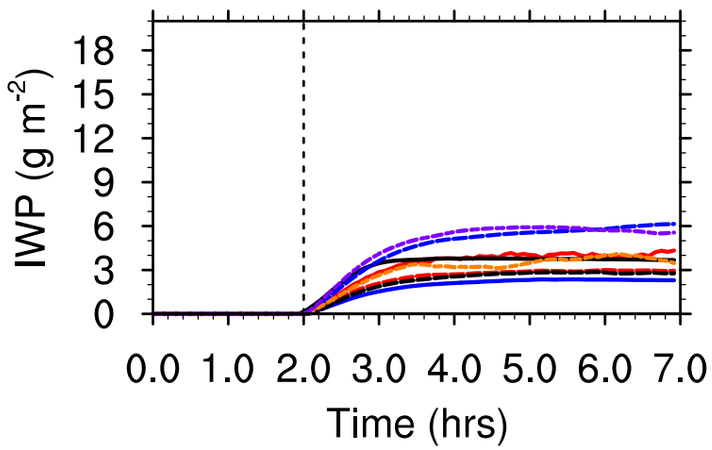
NO ICE

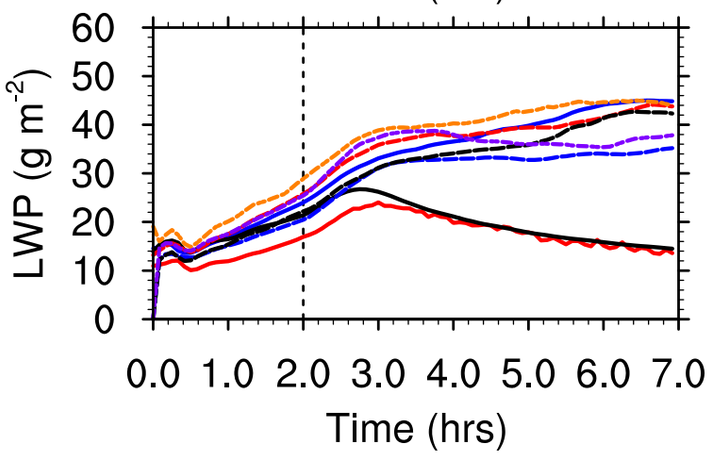
4 L-I











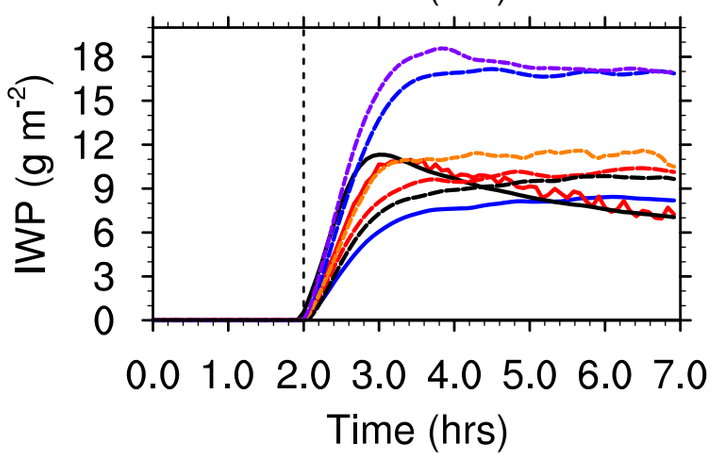


Figure courtesy of Mikhail Ovchinnikov

Ice Nucleation

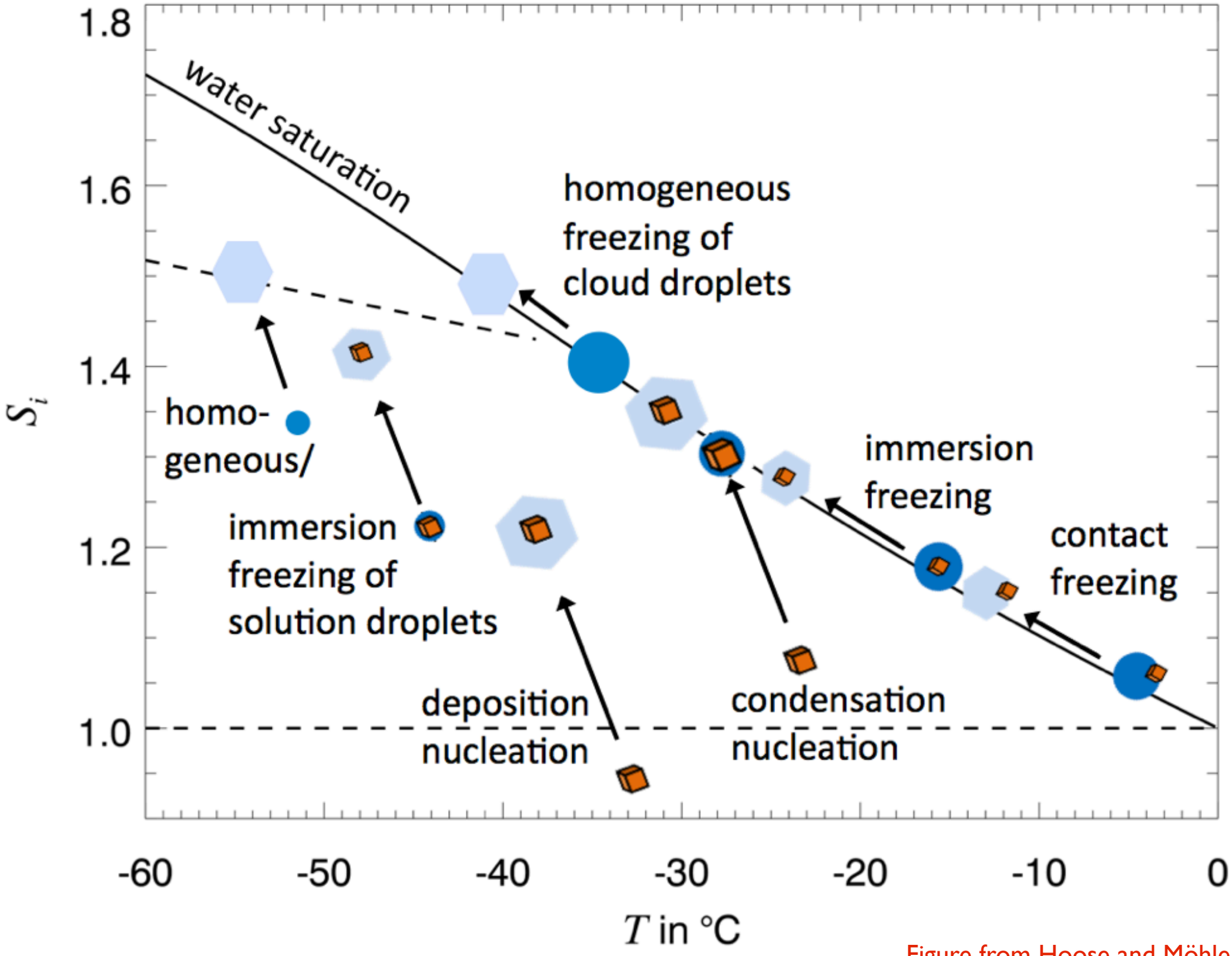


Figure from Hoose and Möhler (2012)

Ice Nucleation (Field Studies)

What do we know? (M-PACE, Prenni et al., 2009)

- Arctic IN concentrations lower than at low latitudes
- M-PACE had extended periods where no IN were detected (91% of the time)
- Ice nucleation mainly through immersion/condensation modes
- Maximum IN concentrations found at or above cloud level, and above the boundary layer.
- Metal oxides and dust dominated the aerosol composition.
- There appears to be a seasonal cycle of IN, based on limited datasets.

What do we know? (ISDAC, McFarquhar et al., 2011; Jackson et al., 2012)

- Ice nuclei concentrations for ISDAC were variable (including 53% below noise floor).
- Ice nucleation during ISDAC came from both the immersion/condensation modes and deposition mode.
- IN were found to contain metals or dust and a significant number were as small as 100 nm.

Ice Nucleation (Field Studies)

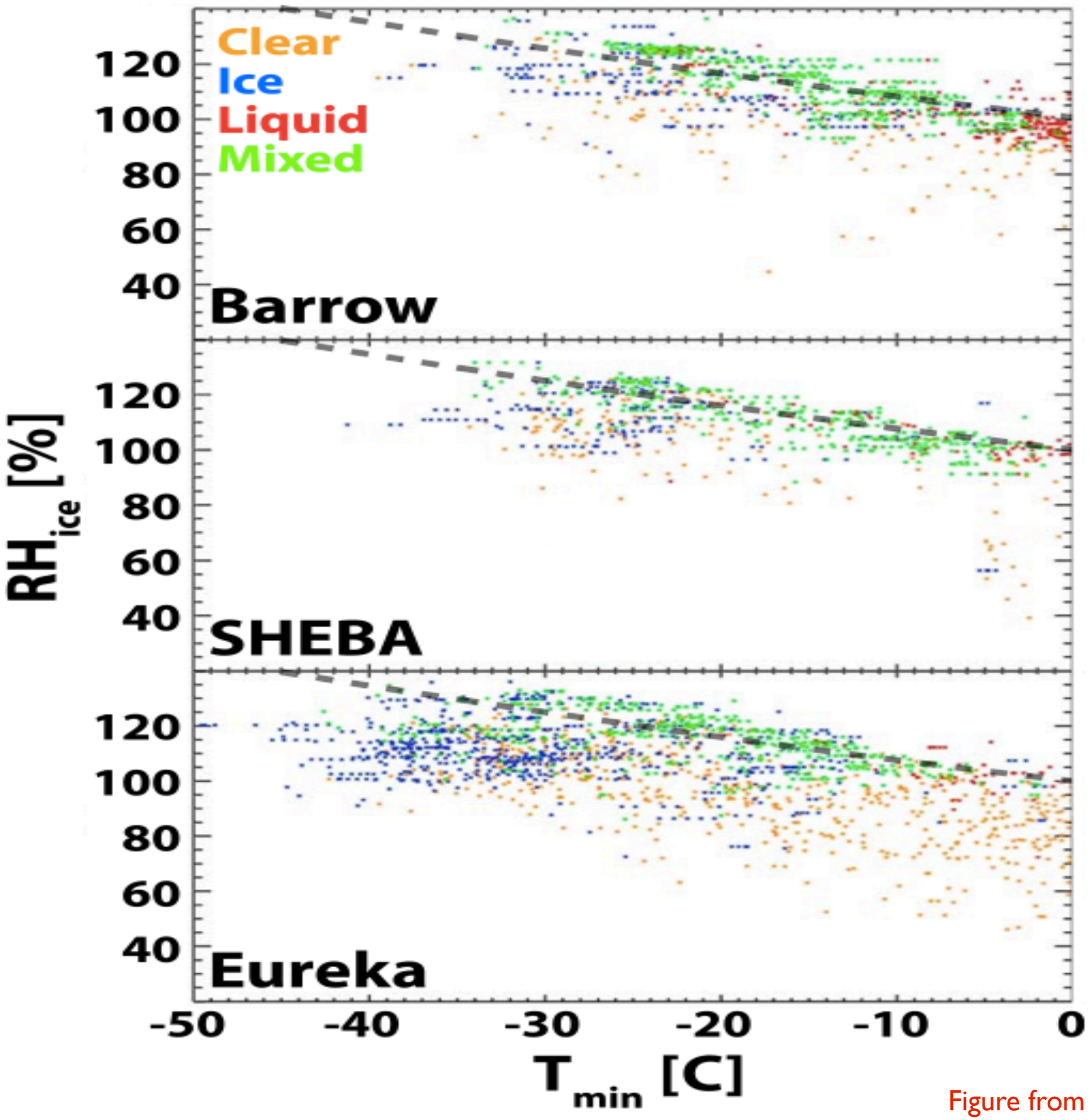


Figure from de Boer et al. (2011)

Ice Nucleation (Field Studies)

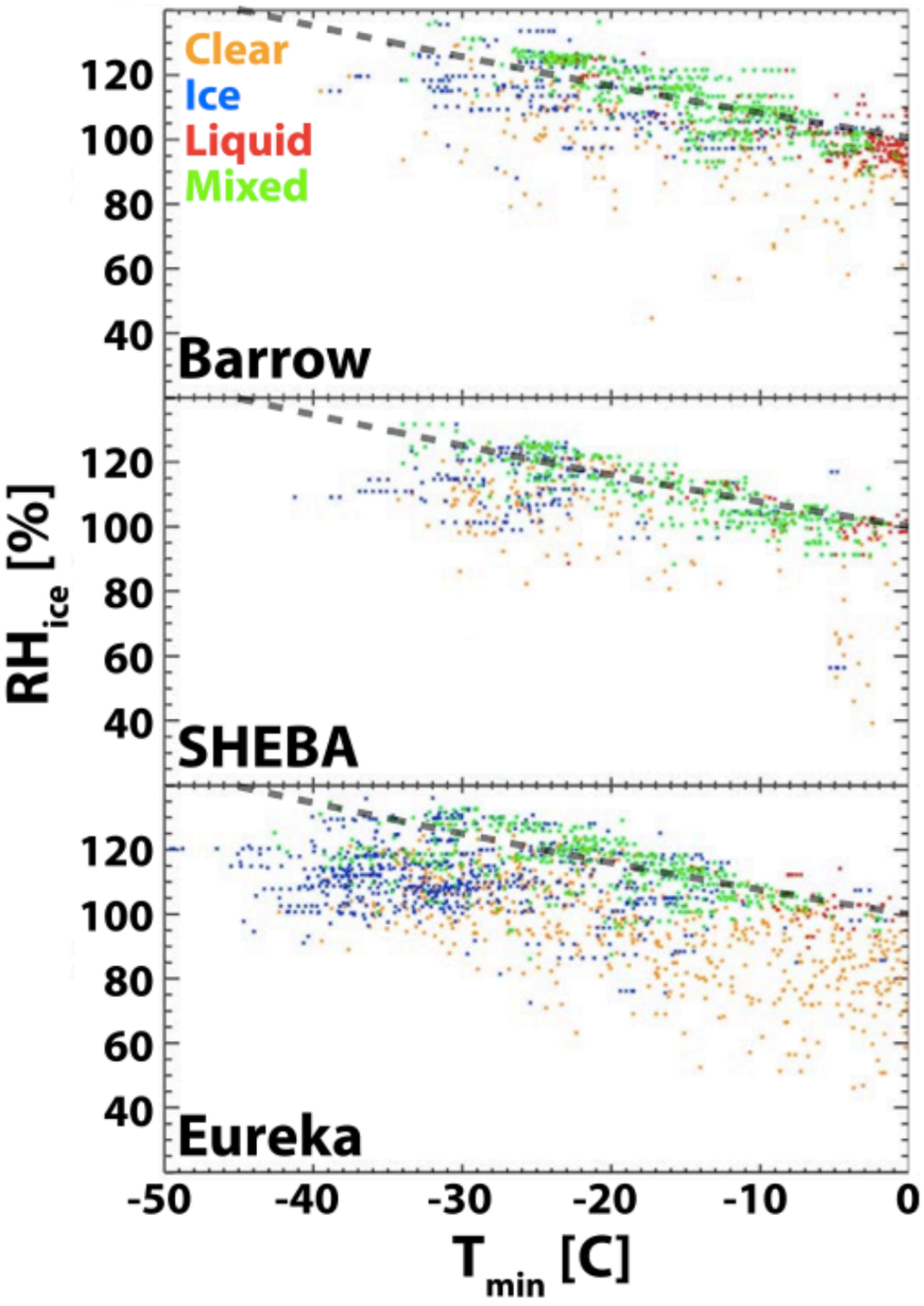


Figure from de Boer et al. (2011)

Can we improve and expand upon efforts such as this?

- Additional sampling of atmospheric temperature and humidity using soundings or UAVs...

- Utilize tethersondes (e.g. Lawson et al., 2011) equipped with ice particle imagers and thermodynamic sensors...

- Use the new scanning ARM instrumentation to expand this sort of climatology...

- Use of near surface measurements...

Ice Nucleation Mode

ISDAC

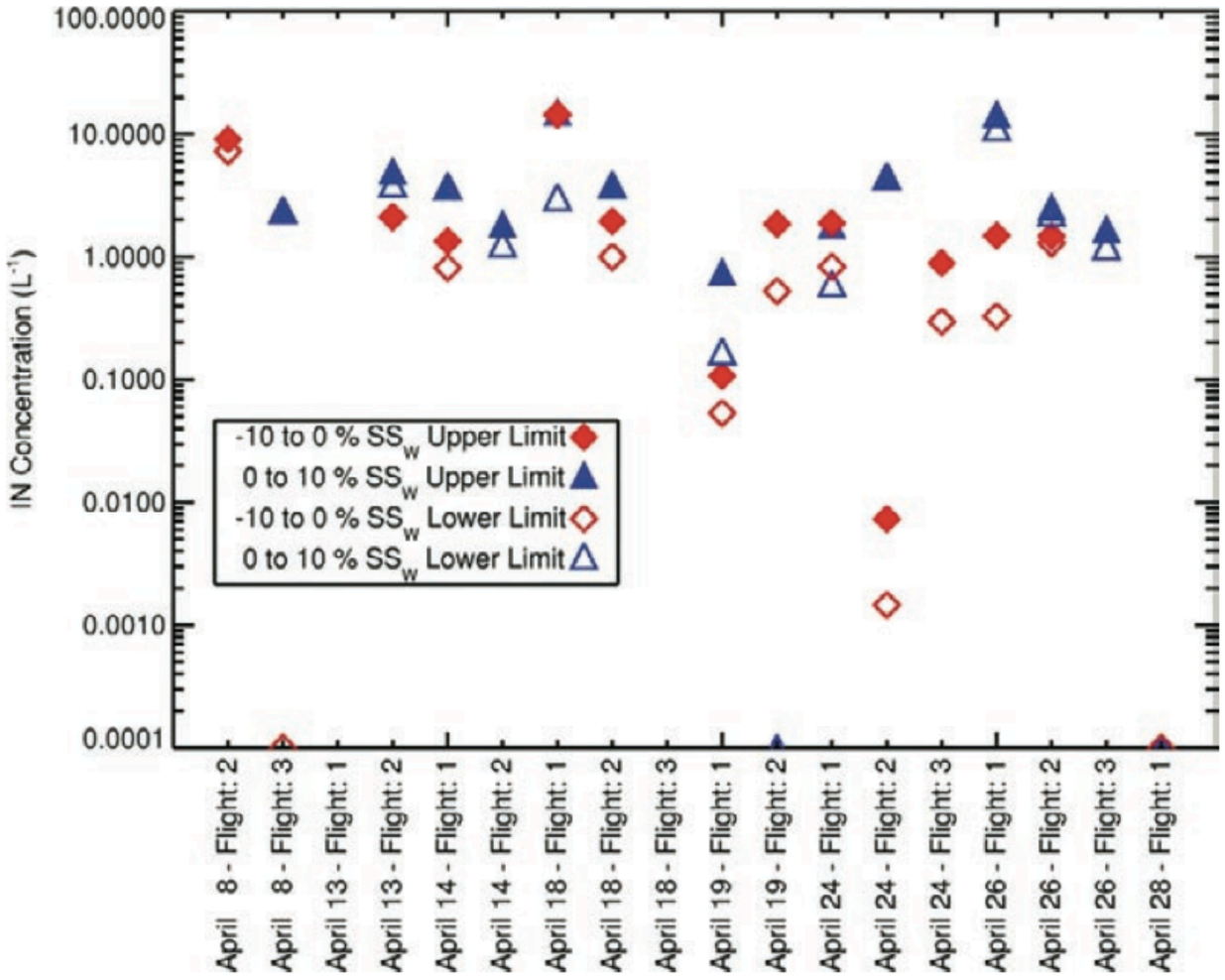


Figure from McFarquhar et al., 2011

MPACE

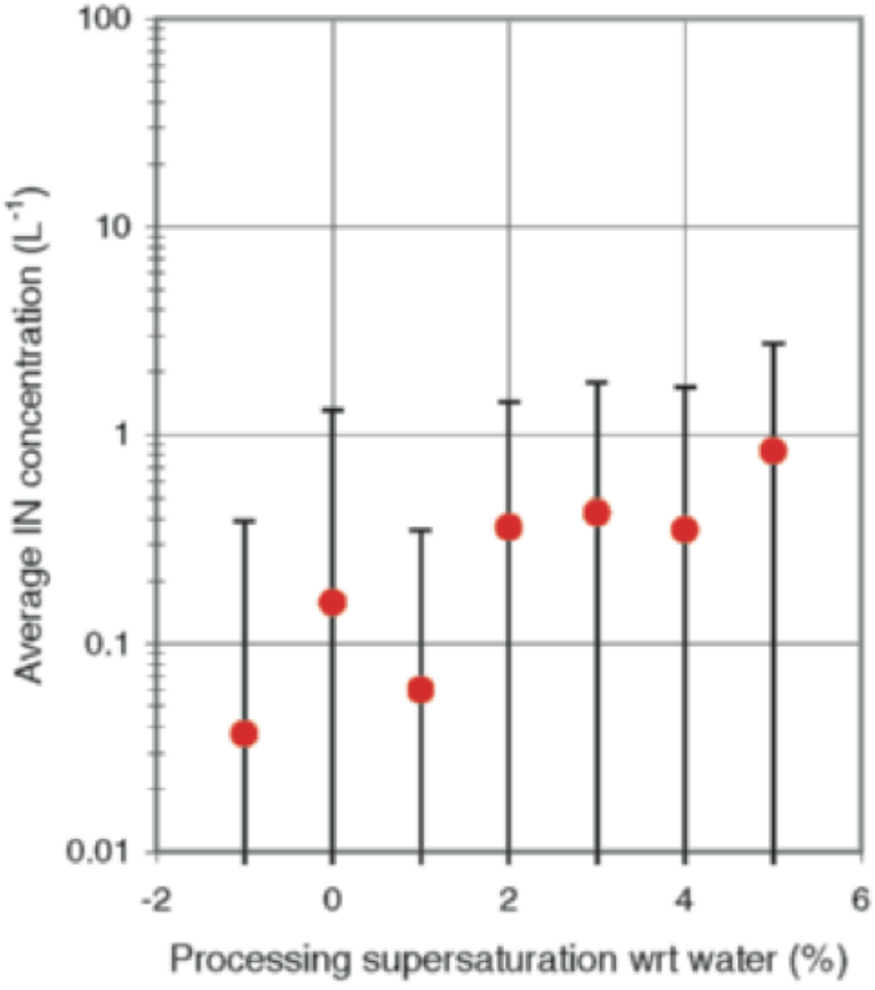


Figure from Prenni et al., 2011

Ice Nucleation Mode

ISDAC

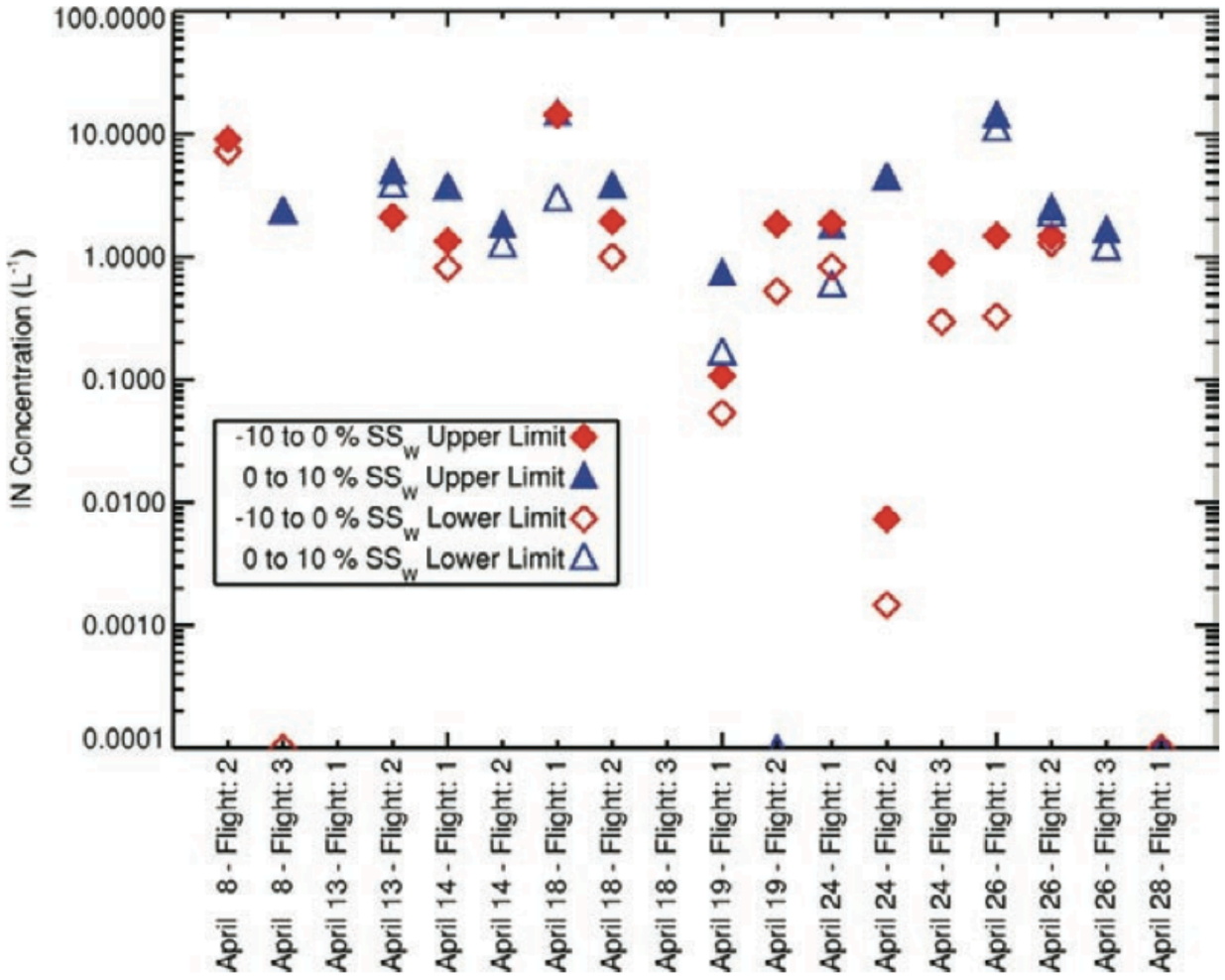


Figure from McFarquhar et al., 2011

MPACE

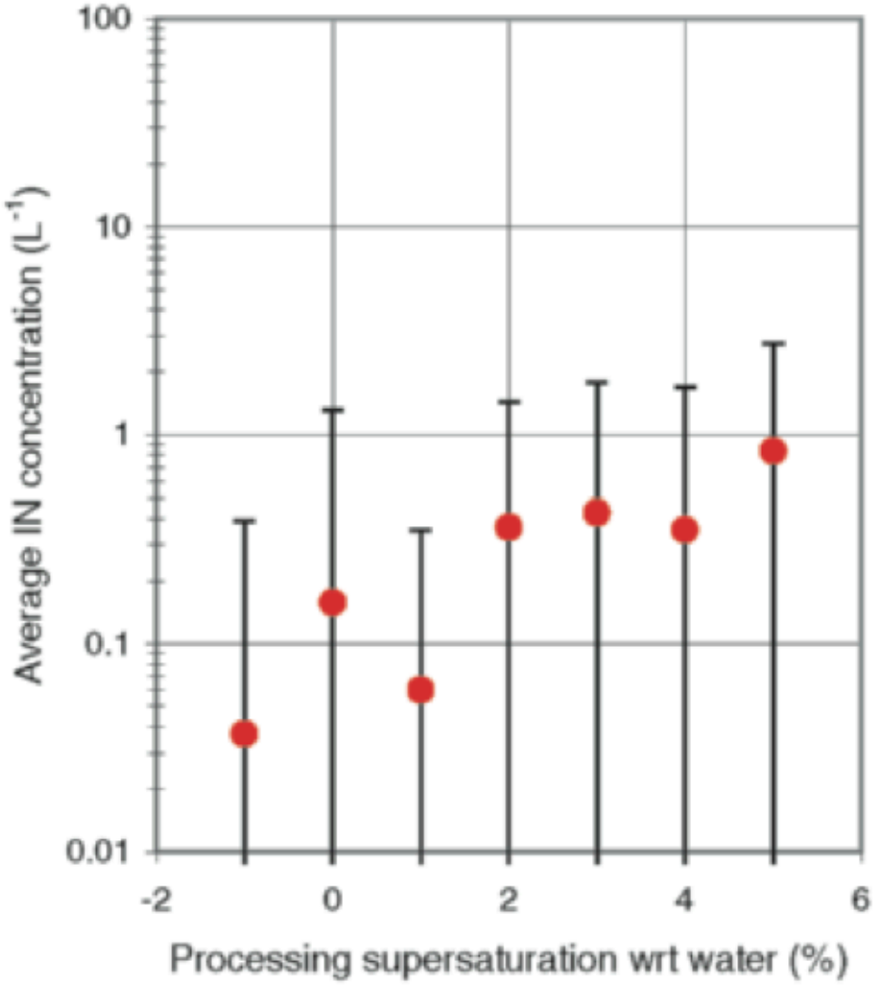


Figure from Prenni et al., 2011

Ultimately, does ice nucleation mode matter for GCMs?

The Role of Liquid Water

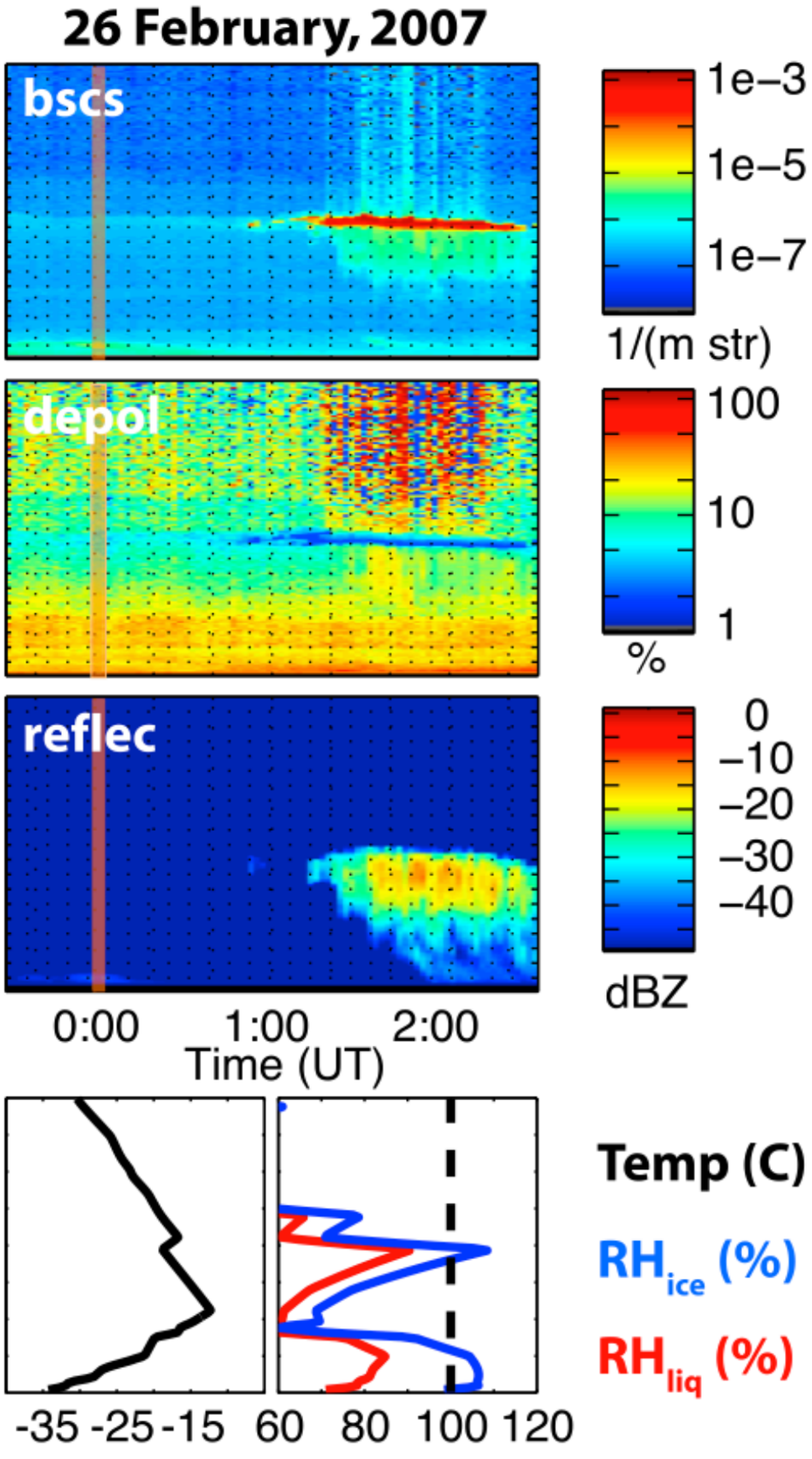


Figure from de Boer et al. (2011)

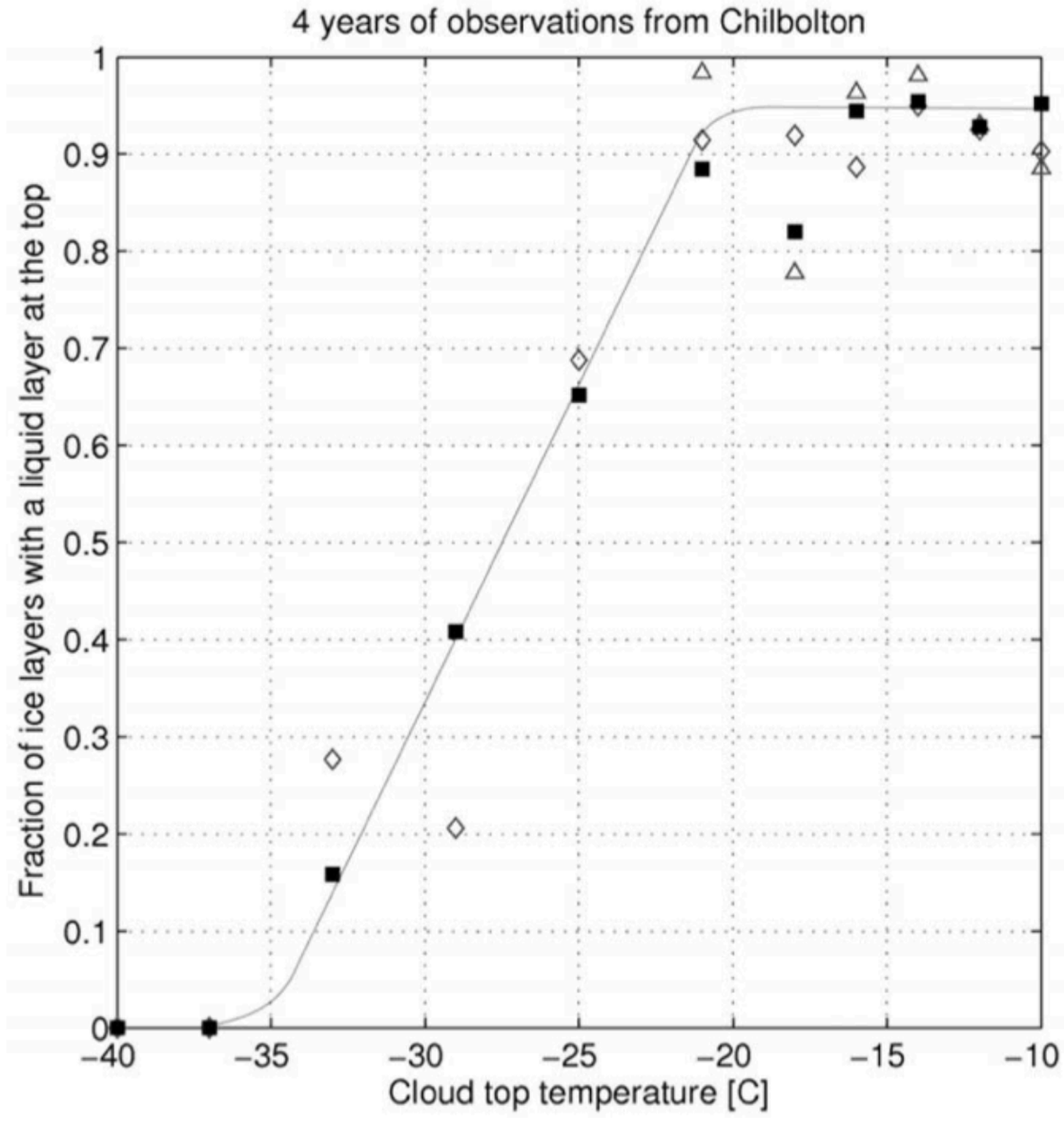


Figure from Westbrook and Illingworth (2011)

The Role of Liquid Water

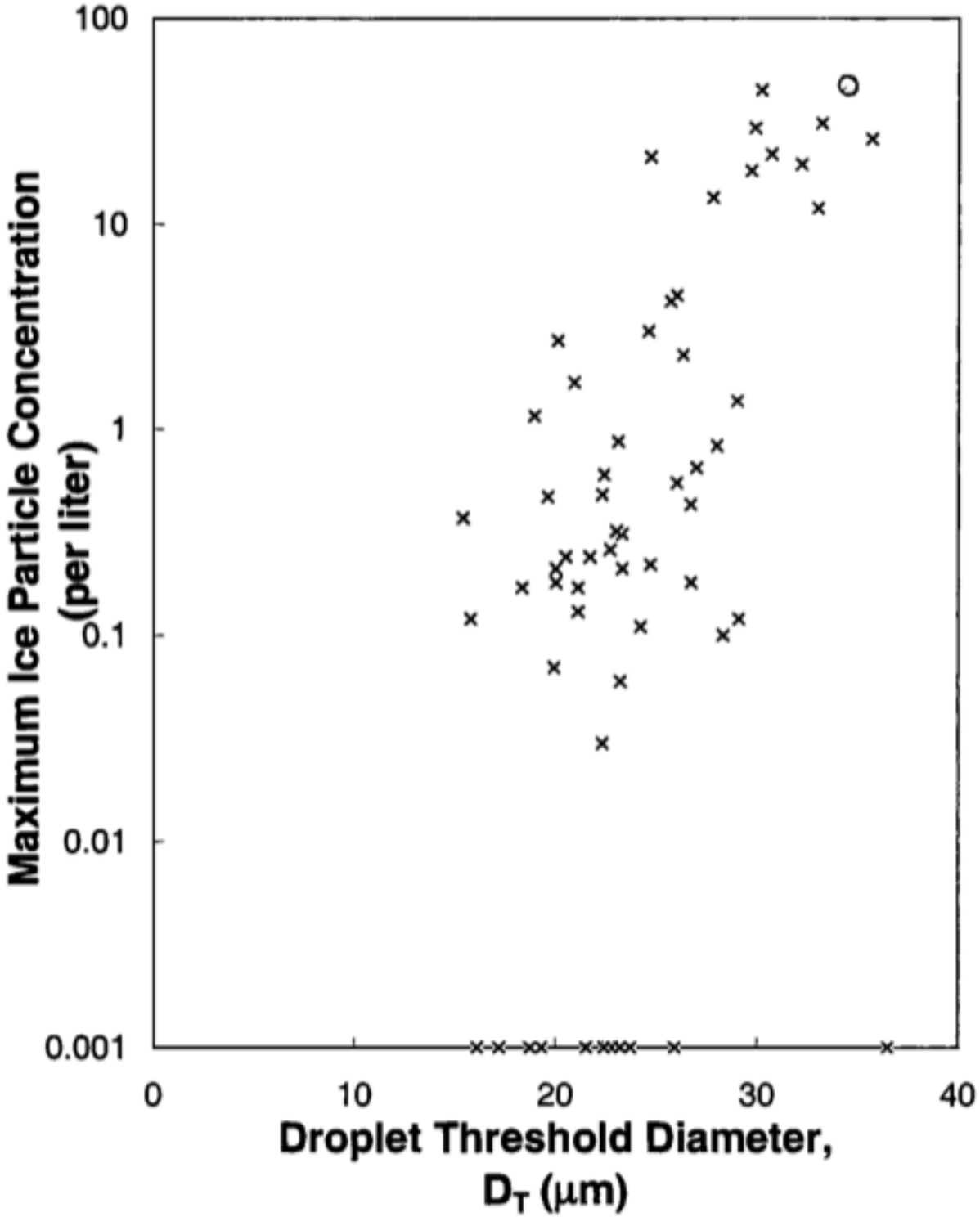


Figure from Rangno and Hobbs (2001)

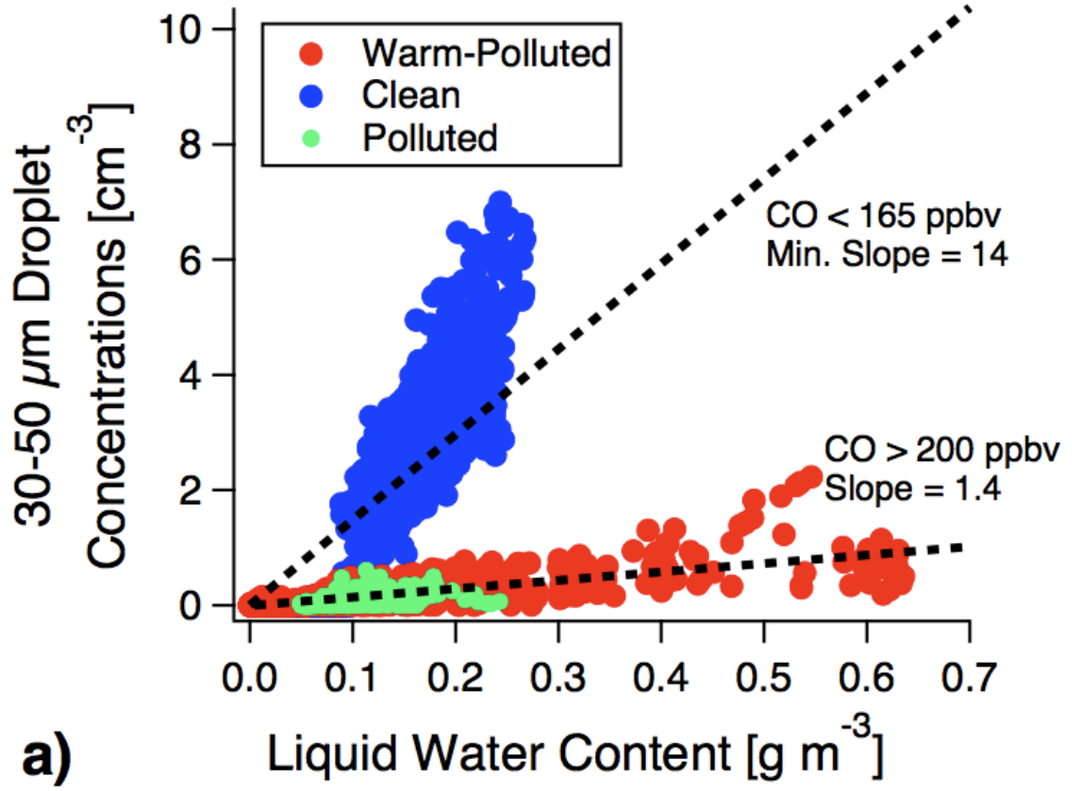
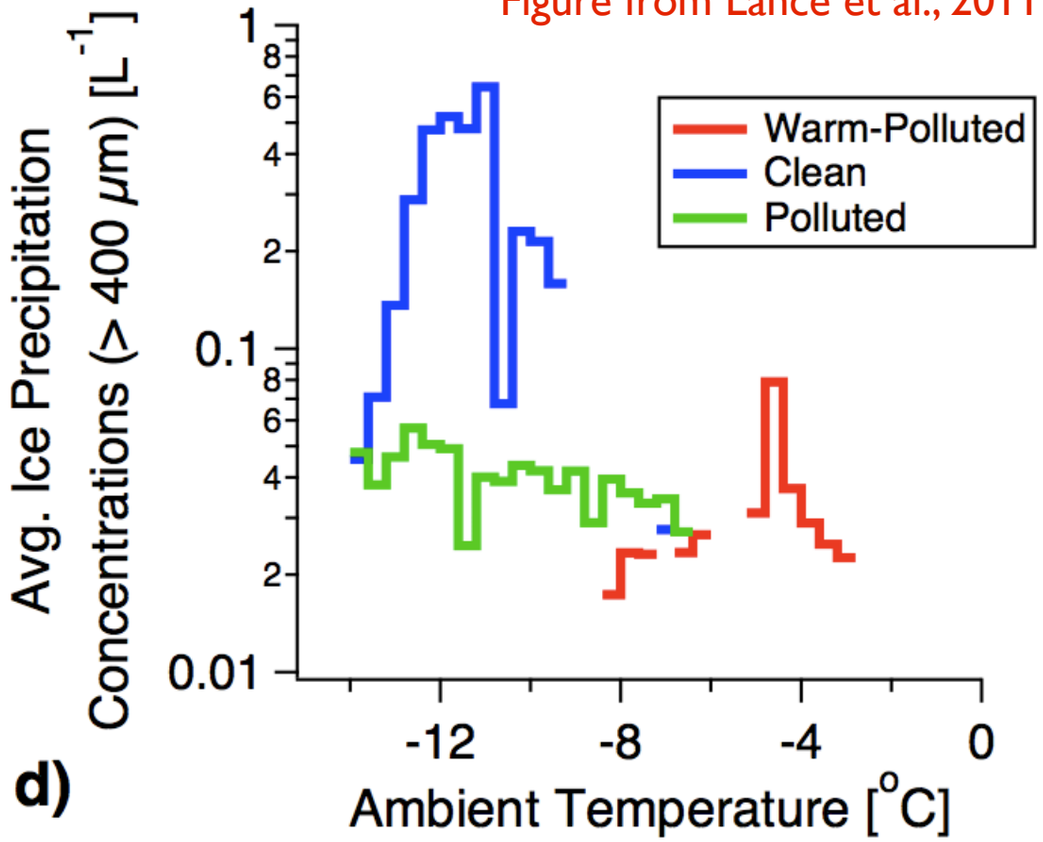


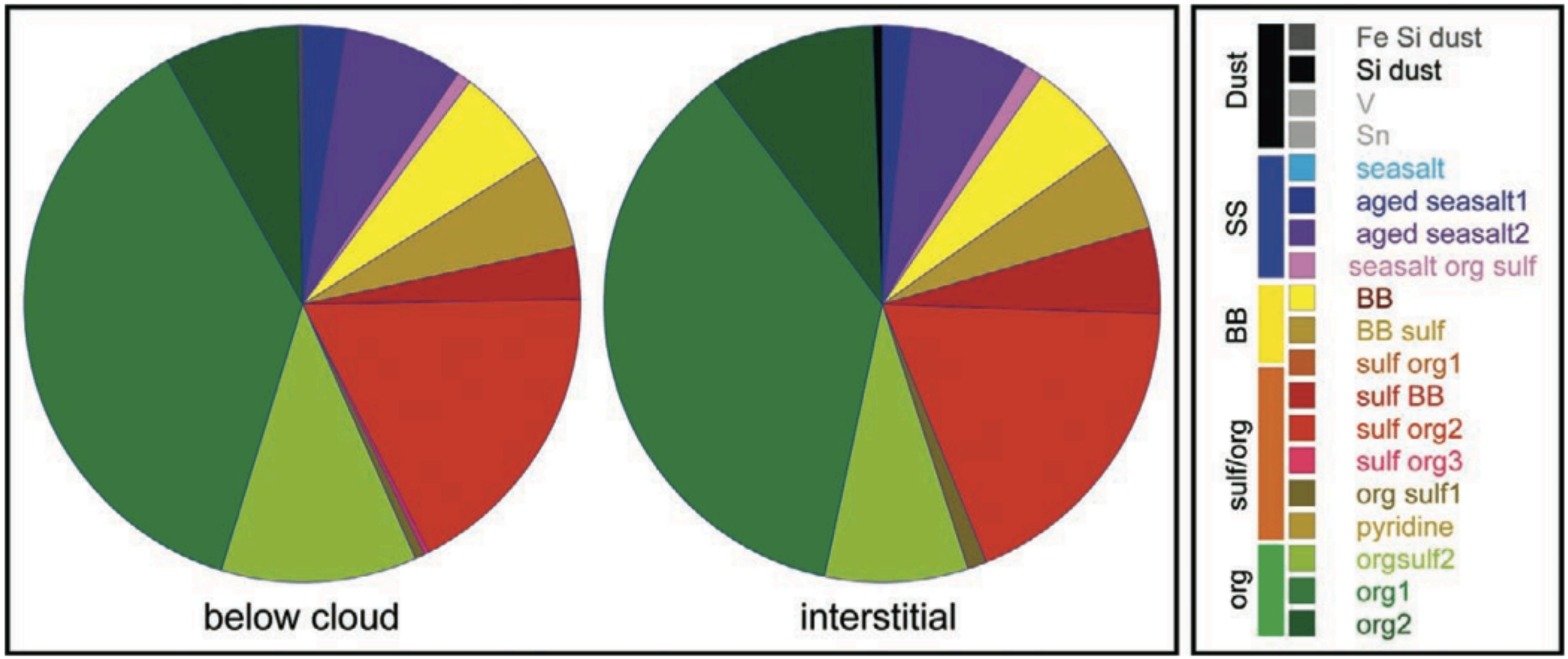
Figure from Lance et al., 2011



The Role of Aerosol Properties

ISDAC

Figure from McFarquhar et al., 2011



Can we, over long timescales, derive statistics on aerosol composition, and aerosol properties, including their ability to nucleate ice and liquid?

Influence of the Large Scale

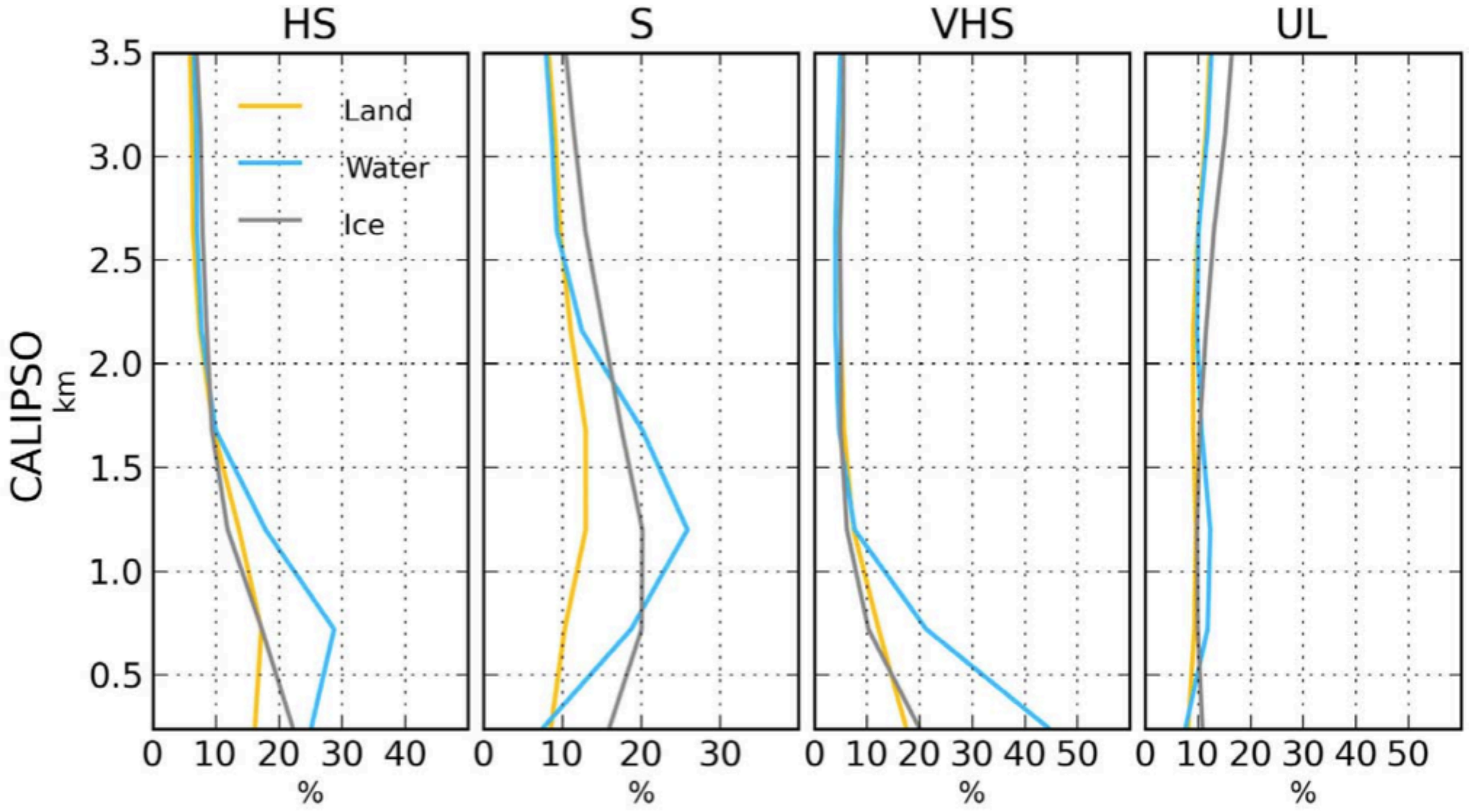


Figure from Barton et al. (2012)

Influence of the Large Scale

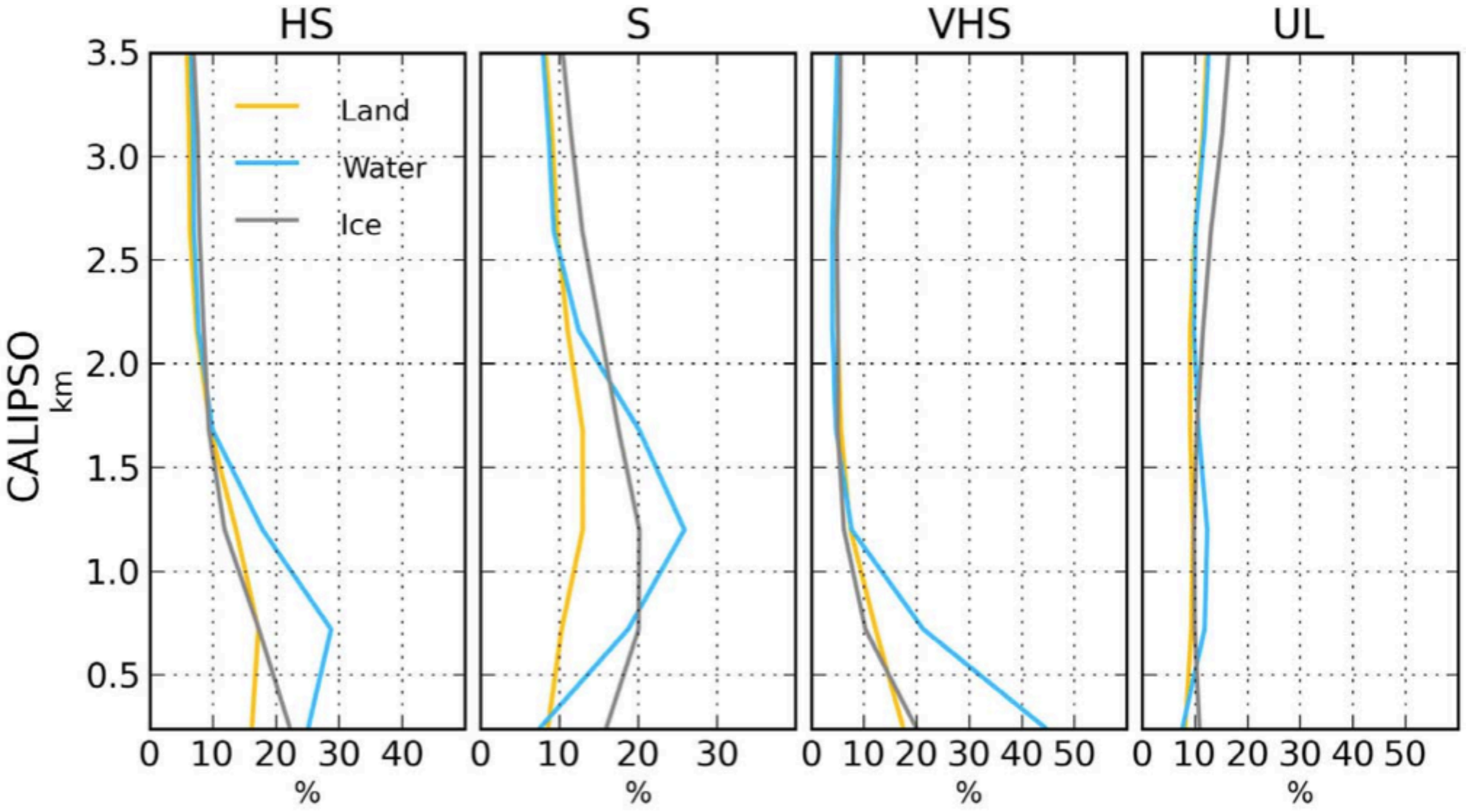


Figure from Barton et al. (2012)

Can we characterize the large-scale conditions linked with the occurence of mixed-phase clouds (or hydrometeor phase in general)?

Open Questions

Targets for Progress?

- Ice nucleation -- Can we actually hope to tackle this?

- Detailed climatology of phase occurrence in the atmosphere

- Characterization of aerosol properties, including profiles and the connection to hydrometeor phase

- What is the role of liquid water on ice formation and growth?

- Closing the aerosol budget in numerical simulation

- Influence of large scale advection of heat, moisture and aerosols on cloud phase and occurence

- Ice crystal growth and development

References

Bigg, E.K. (1980): Comparison of aerosol at four baseline atmospheric monitoring stations, *J. Appl. Meteor.*, **19**, 521-533.

Brasseur, Guy P.; Prinn, Ronald G.; Pszenny, Alexander A.P. (2003): Atmospheric Chemistry in a Changing World, Springer, 300 p.

Cesana, G., J. E. Kay, H. Chepfer, J. English, and G. de Boer (2012): Ubiquitous low-level liquid-containing Arctic clouds: New observations and climate model constraints from CALIPSO-GOCCP, Geophys. Res. Lett., doi:10.1029/2012GL053385, in press.

de Boer, G., H. Morrison, M.D. Shupe and R. Hildner (2011): Evidence of Liquid-Dependent Ice Nucleation in High-Latitude Stratiform Clouds from Surface Remote Sensors, *Geophys. Res. Lett.*, **38**, L01803.

de Boer, G., T. Hashino, G.J. Tripoli and E.W. Eloranta (2012a): A numerical study of aerosol influence on mixed-phase stratiform clouds through modulation of the liquid phase, *Atmos. Chem. Phys.*, submitted.

de Boer, G., P.O.G. Persson, M.D. Shupe, P.M. Caldwell, J.S. Boyle, S.A. Klein and M. Tjernstrom (2012b): Near-Surface Meteorology During ASCOS: Evaluation of Representation in Reanalyses and CAM5, *Atmos. Chem. Phys.*, in preparation.

Ervens, B. G. Feingold, K. Sulia and J.Y. Harrington (2011): The impact of microphysical parameters, ice nucleation mode, and habit growth on the ice/liquid partitioning in mixed-phase Arctic clouds, *J. Geophys. Res.*, **116**, D17205.

Fridlind, A.M., B. Van Diedenhoven, A.S. Ackerman, A. Avramov, A. Mrowiec, H. Morrison, P. Zuidema and M.D. Shupe (2012): A FIRE-ACE/SHEBA case study of mixed-phase Arctic boundary layer clouds: Entrainment rate limitations on rapid primary ice nucleation processes, *J. Atmos. Sci.*, **69**, 365-389.

Gettelman, A., X. Liu, S. J. Ghan, H. Morrison, S. Park, A. J. Conley, S. A. Klein, J. Boyle, D. L. Mitchell, and J.-L. F. Li (2010), Global simulations of ice nucleation and ice supersaturation with an improved cloud scheme in the Community Atmosphere Model, *J. Geophys. Res.*, **115**, D18216,

Harrington, J.Y., and P.Q. Olsson (2001): On the potential influence of ice nuclei on surface-forced marine stratocumulus cloud dynamics. *J. Geophys. Res.*, **106**, 27473-27484.

Hobbs, P.V. and A.L. Rangno (1985): Ice particle concentrations in clouds, *J. Atmos. Sci.*, **42**, 2523-2549.

Hoose, C. and O. Möhler (2012): Heterogeneous ice nucleation on atmospheric aerosols: a review of results from laboratory experiments, *Atmos. Chem. Phys. Discuss.*, **12**, 12531-12621.

Jackson, R.C., G.M. McFarquhar, A.V. Korolev, M.E. Earle, P.S.K. Liu, R.P. Lawson, S. Brooks, M. Wolde, A. Laskin and M. Freer (2012): The dependence of ice microphysics on aerosol concentration in arctic mixed-phase stratus clouds during ISDAC and M-PACE, *J, Geophys. Res.*, **117**, D15207.

Klein, S., et al. (2009), Intercomparison of model simulations of mixed− phase clouds observed during the ARM Mixed−Phase Arctic Cloud Experiment. Part I: Single layer cloud, Q. J. R. Meteorol. Soc., 135, 979–1002.

Lance, S., M.D. Shupe, G. Feingold, C.A. Brock, J. Cozic, J.S. Holloway, R.H. Moore, A. Nenes, J.P. Schwarz, J.R. Spackman, K.D. Froyd, D.M. Murphy, J. Brioude, O.R. Cooper, A. Stohl and J.F. Burkhart (2011): Cloud condensation nuclei as a modulator of ice processes in Arctic mixed-phase clouds, *Atmos. Chem. Phys.*, **11**, 8003-8015.

Lawson, R.P., K. Stamnes, J. Stamnes, P. Zmarzly, J. Koskuliks, C. Roden, Q. Mo, M. Carrithers and G.L. Bland (2011): Deployment of a tethered-balloon system for microphysics and radiative measurements in mixed-phase clouds at Ny-Alesund and South Pole, *J. Atmos. Ocean. Tech.*, **28**, 656-670.

McFarquhar, G.M. et al. (2011): Indirect and semidirect aerosol campaign: The impact of Arctic aerosols on clouds, *Bull. Am. Meteor. Soc.*, **92**, 183-201.

Morrison, H., de Boer, G., G. Feingold, J.Y. Harrington, M.D. Shupe and K. Sulia (2012): Resilience of Persistent Arctic Mixed-Phase Clouds, *Nature Geosci.*, **5**, 11-17.

Morrison, H., P. Zuidema, A. Ackerman, A. Avramov, G. de Boer, J. Fan, A. Fridlind, T. Hashino, J. Harrington, Y. Luo, M. Ovchinnikov, and B. Shipway (2011): Intercomparison of Cloud Model SImulations of Arctic Mixed-Phase Boundary Layer Clouds Observed During SHEBA, *J. Adv. Model. Earth Syst.,* 3, M06003.

Prenni, A.J., J.Y. Harrington, M. Tjernström, P.J. DeMott, A. Avramov, C.N. Long, S. M. Kreidenweis, P.Q. Olsson and J. Verlinde (2007): Can ice-nucleating aerosols affect Arctic seasonal climate? *Bull. Am. Meteor. Soc.*, **88**, 541-550.

Rangno, A.L. and P.V. Hobbs (2001): Ice particles in stratiform clouds in the Arctic and possible mechanisms for the production of high ice concentrations, *J Geophys. Res.*, **106**, 15065-15075.

Shupe, M.D., and J.M. Intrieri (2004): Cloud radiative forcing of the Arctic surface: The influence of cloud properties, surface albedo, and solar zenith angle, *J. Climate*, **17**, 616-628.

Wang, H., R.C. Easter, P.J. Rasch, M. Wang, X. Liu, S.J. Ghan, Y. Qian, J.-H. Yoon, P.-L. Ma and V. Velu (2012): Improving aerosol transport to high-latitudes in the Community Atmosphere Model CAM5, *Atmos. Chem. Phys. Discuss.*, in press.

Westbrook, C.D. and A.J. Illingworth (2011): Evidence that ice forms primarily in supercooled liquid clouds at temperatures > -27C, *Geophys. Res. Lett.*, **38**, L14808.

Open Questions

Targets for Progress?

- Ice nucleation -- Can we actually hope to tackle this?

- Detailed climatology of phase occurrence in the atmosphere

- Characterization of aerosol properties, including profiles and the connection to hydrometeor phase

- What is the role of liquid water on ice formation and growth?

- Closing the aerosol budget in numerical simulation

- Influence of large scale advection of heat, moisture and aerosols on cloud phase and occurence

- Ice crystal growth and development

EXTRA SLIDES

CMIP5 Models

FGOALS-g2

GFDL-ESM2G

GISS-E2-R

HadGEM2-ES

inmcm4

IPSL-CM5A-MR

MIROC4h

MRI-CGCM3

NorESM1-M

CCSM4

Relevance of Phase

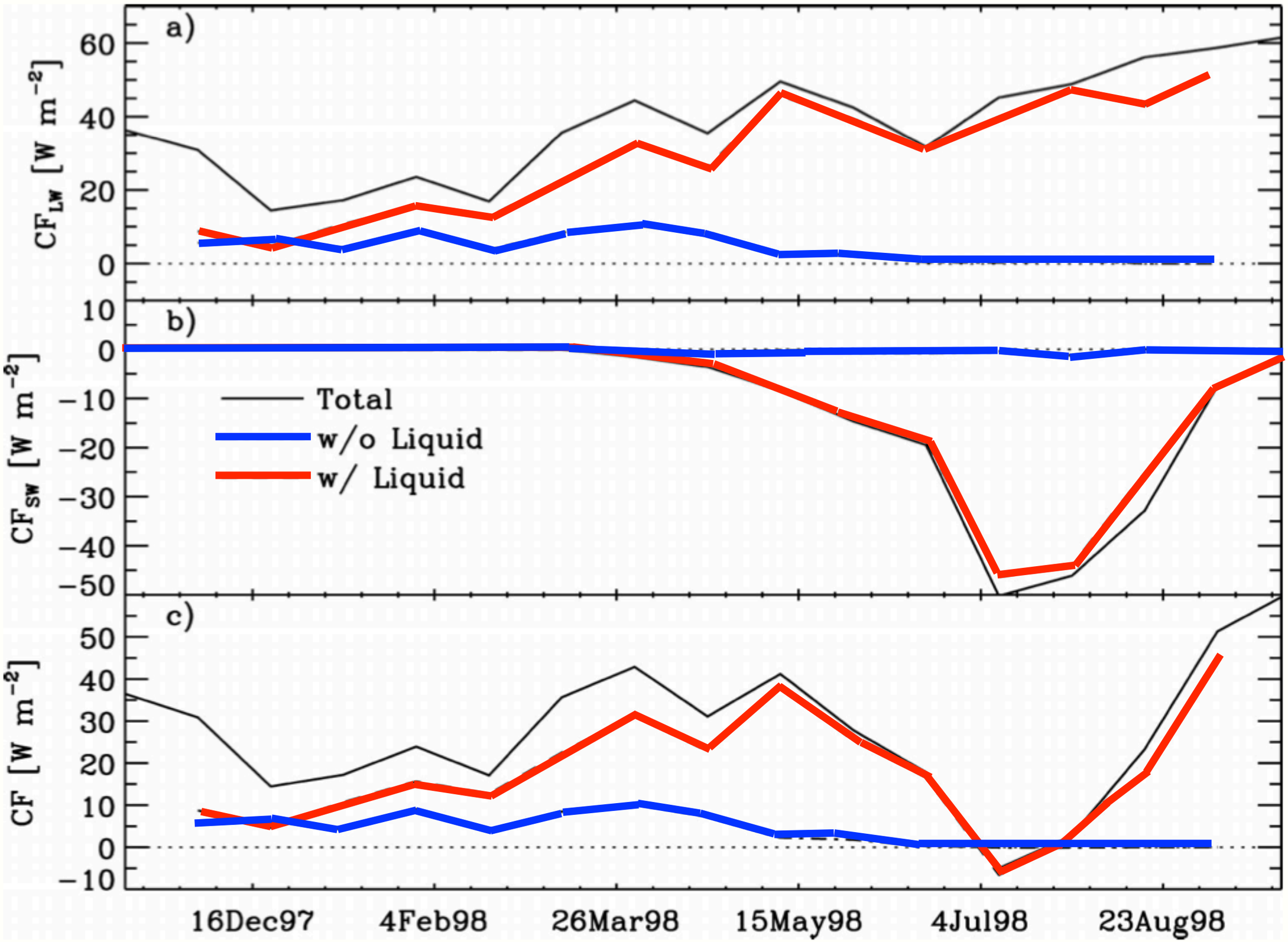
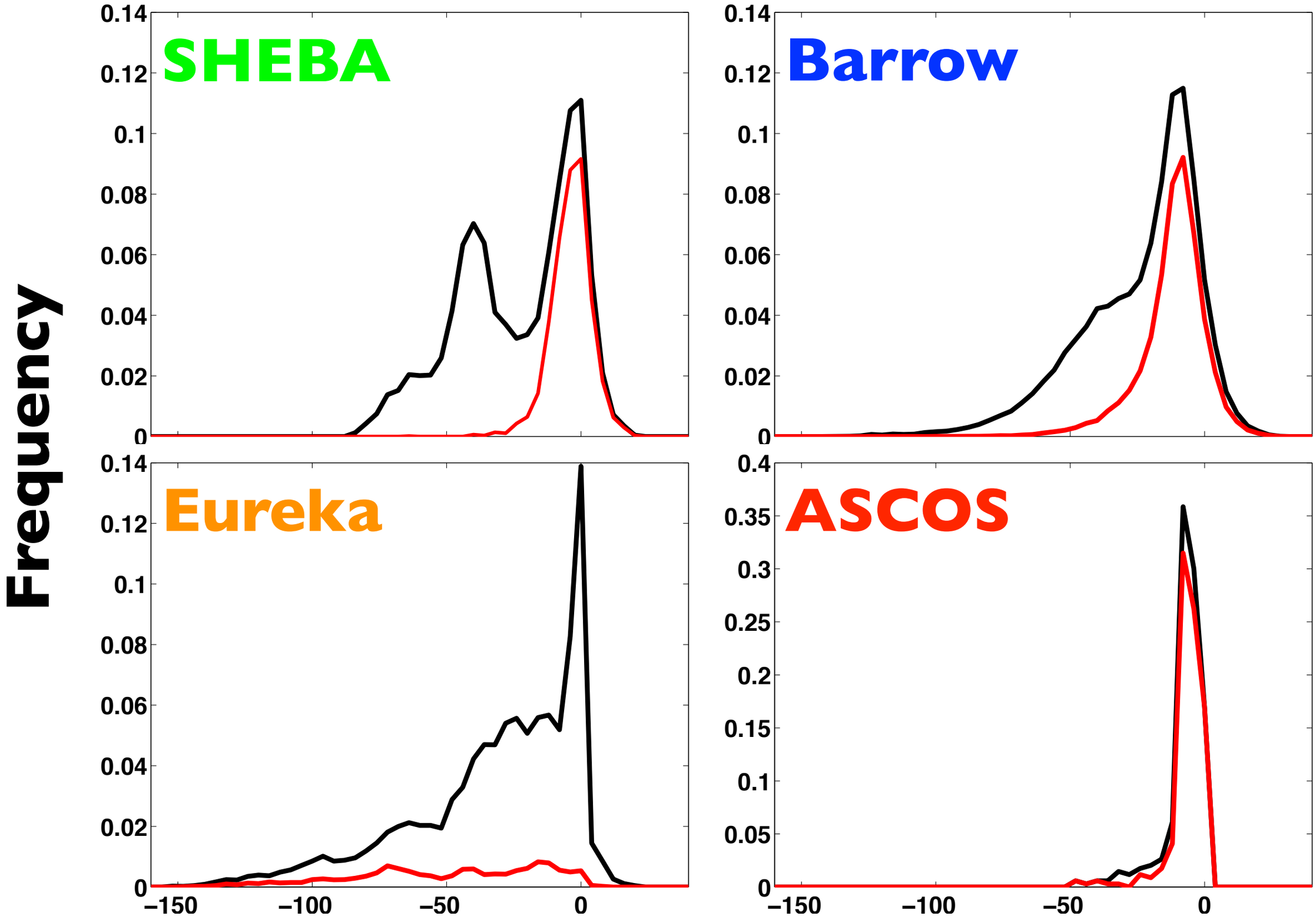


Figure from Shupe and Intrieri (2004)

What's the Cause?



The Role of Aerosols

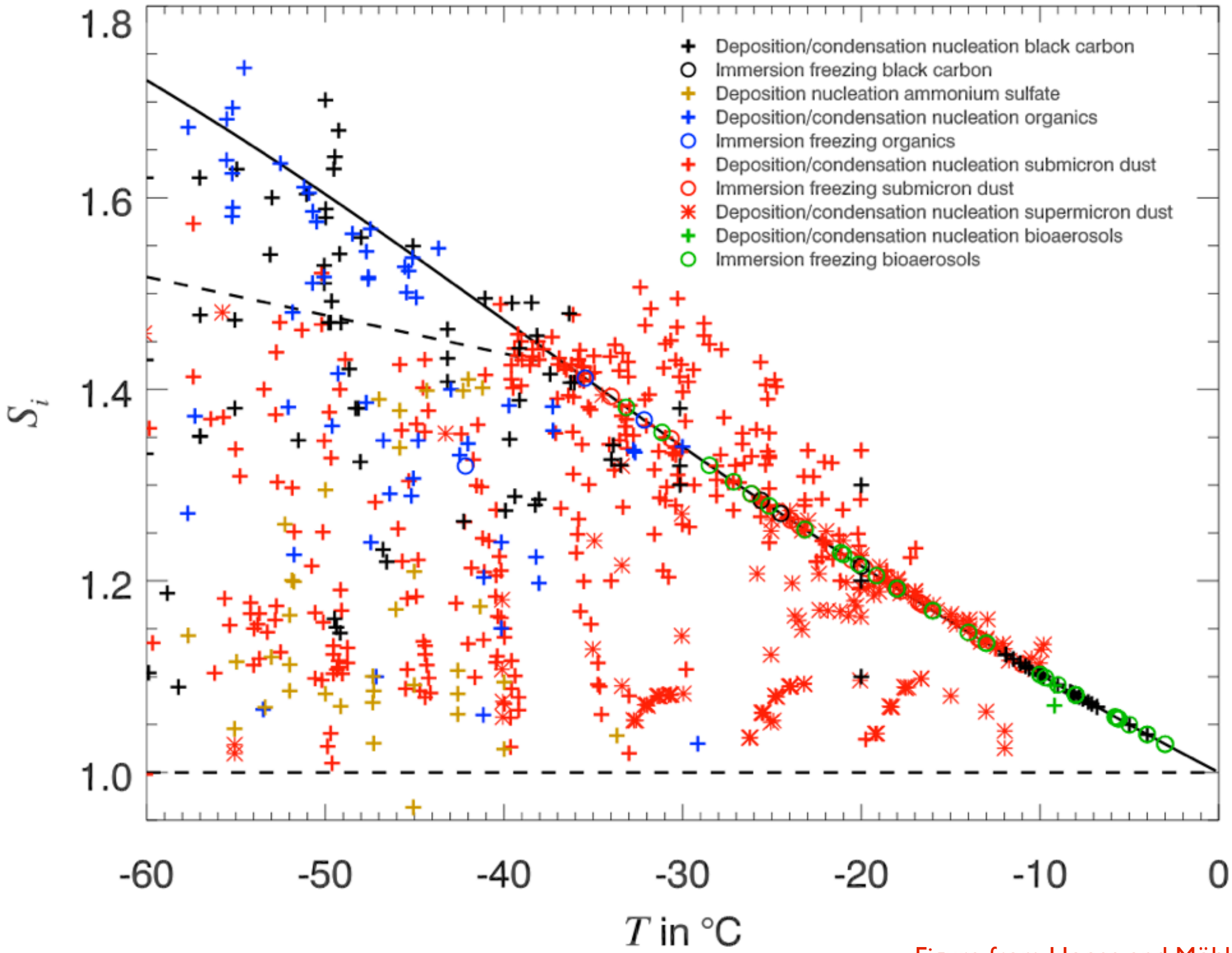


Figure from Hoose and Möhler (2012)

Model-Intercomparison Driven Campaign?

Can we design a measurement campaign that is specifically designed around what we've learned from the model intercomparisons?

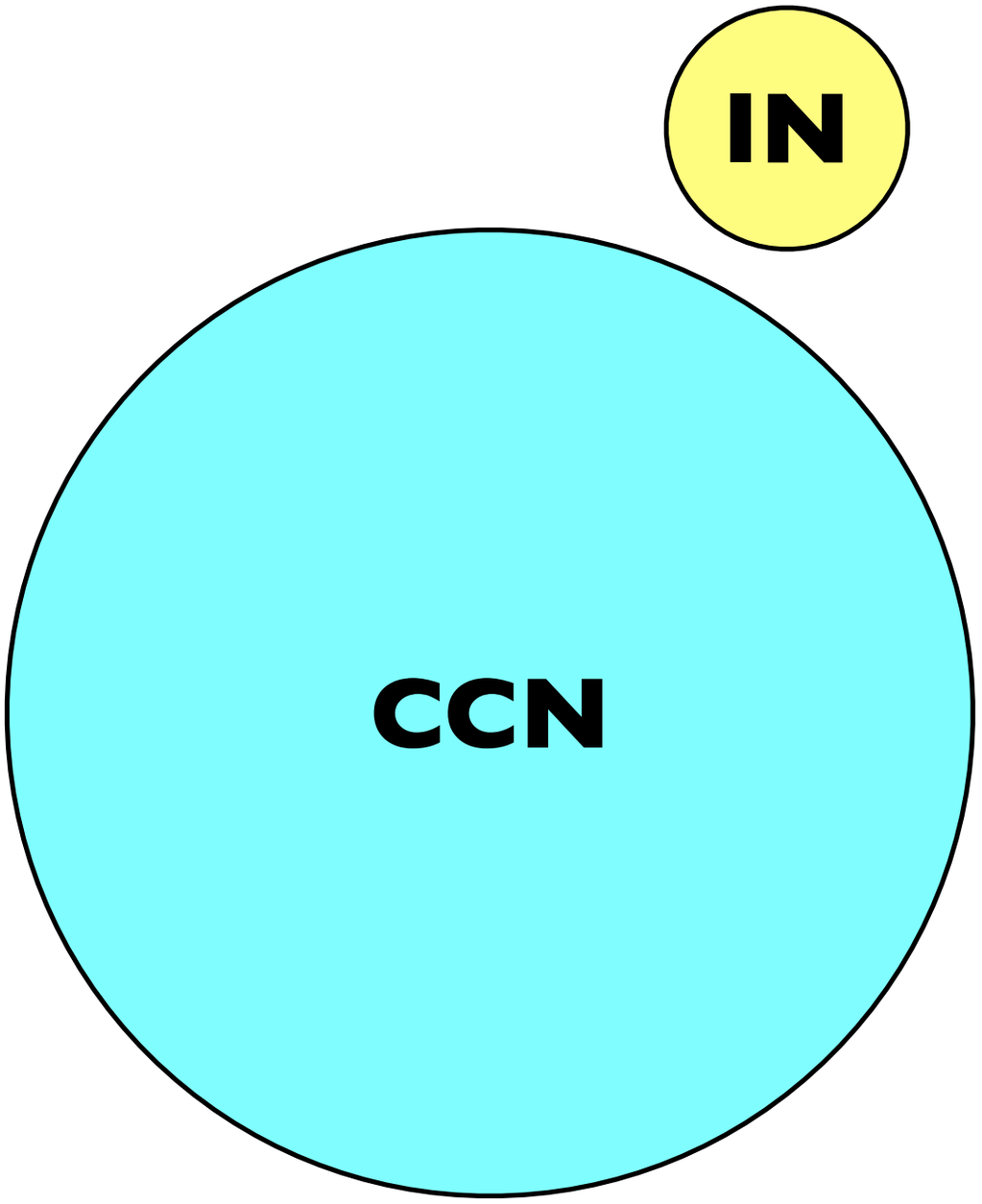
What key variables do we need?

- Detailed information on evolution of temperature and moisture structure and large-scale advection of these terms

- Detailed aerosol information, including IN concentrations, CCN properties, aerosol composition

-

Modeling Paradigms



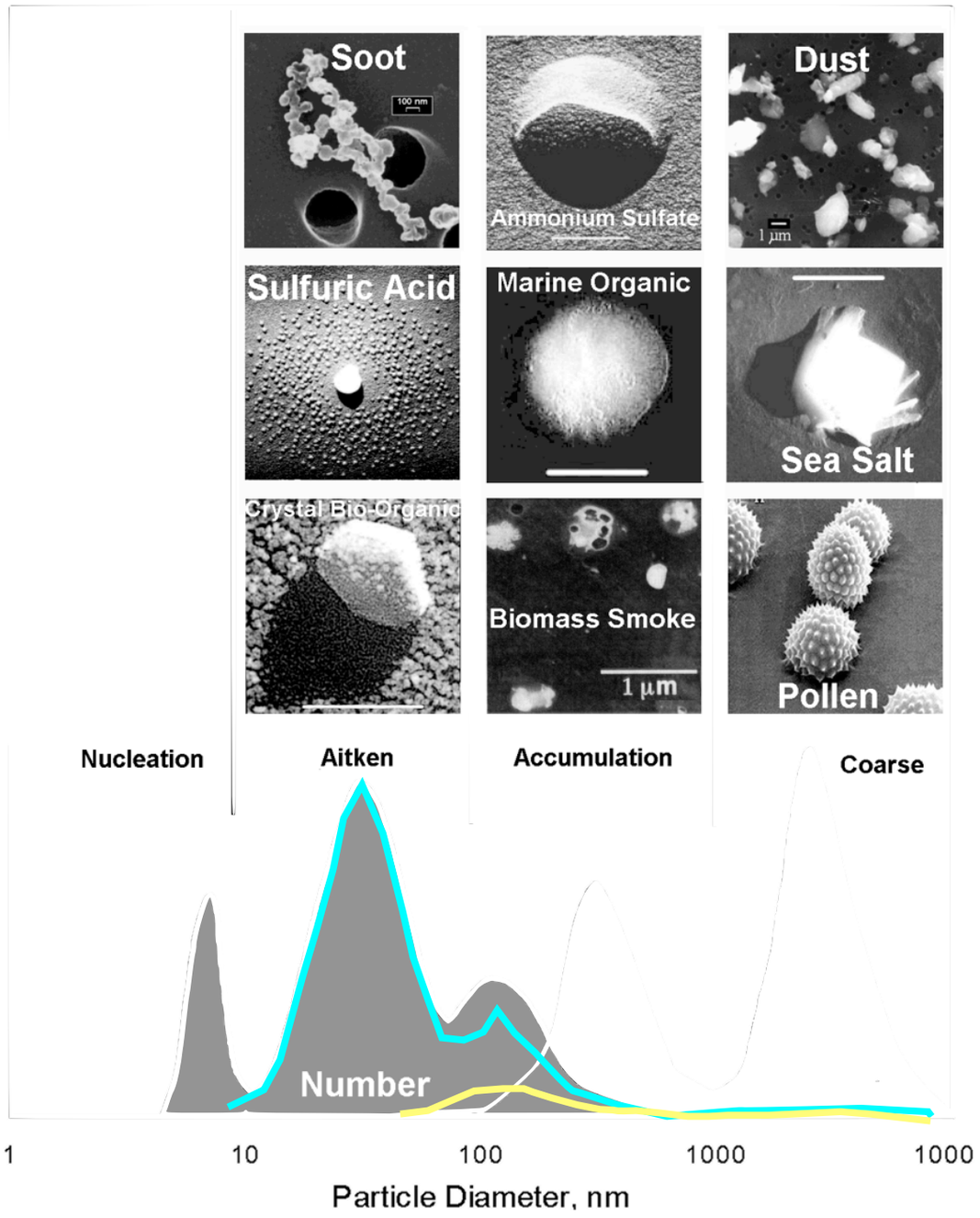
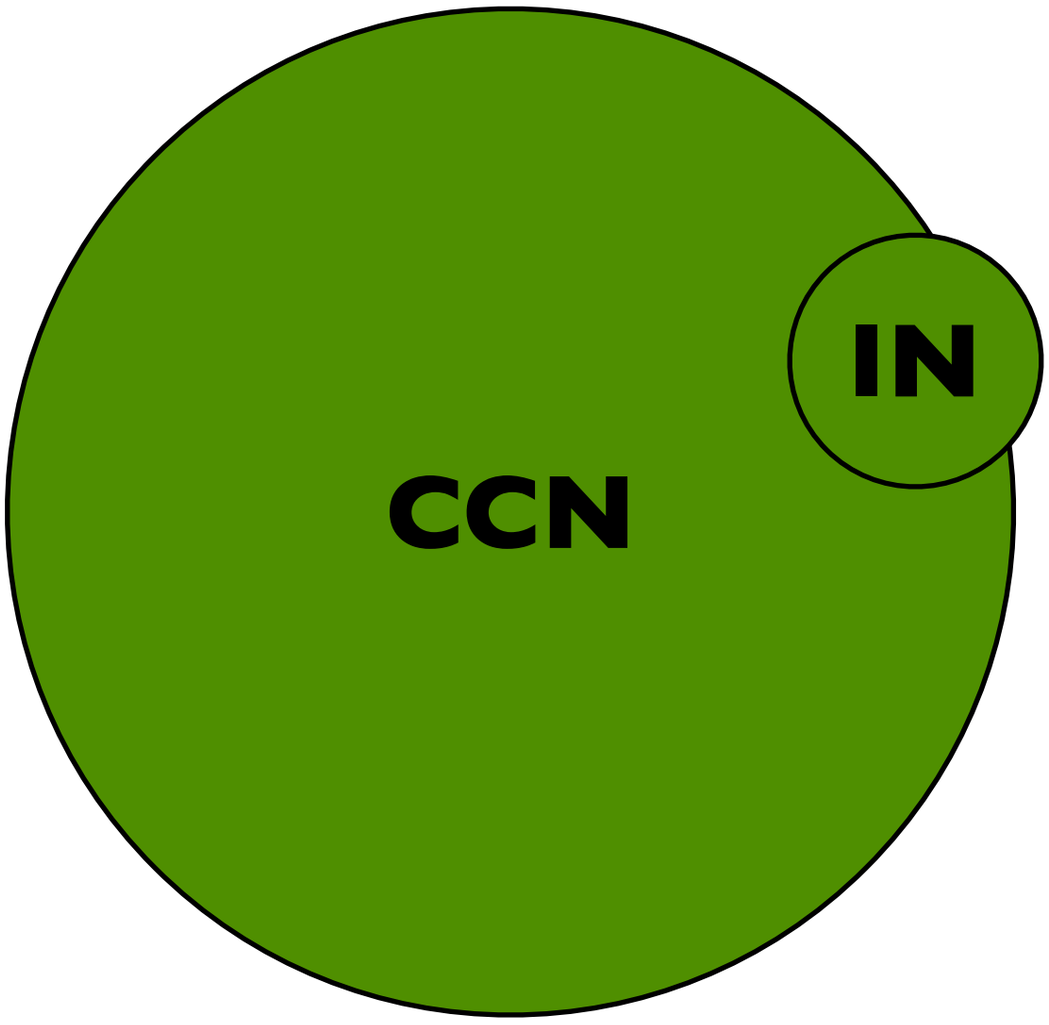
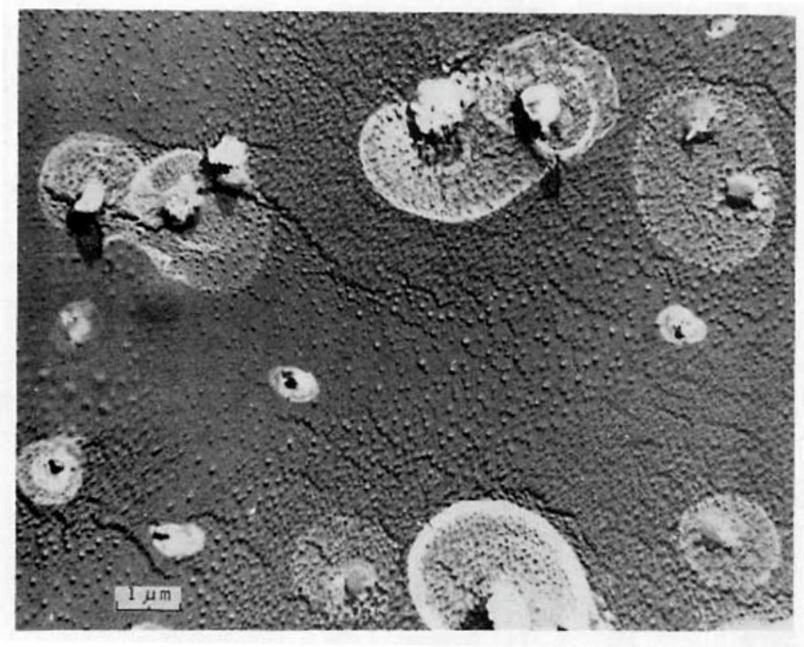
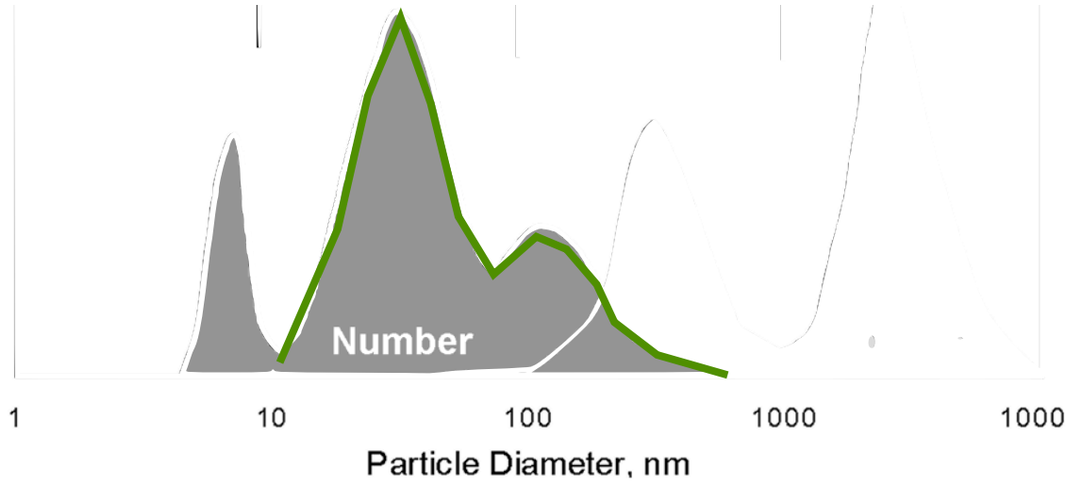


Figure from Brasseur et al. (2003, modified)

Modeling Paradigms







Figures from Bigg (1980, top) and Brasseur et al. (2003, bottom, modified)

Relevance of Phase

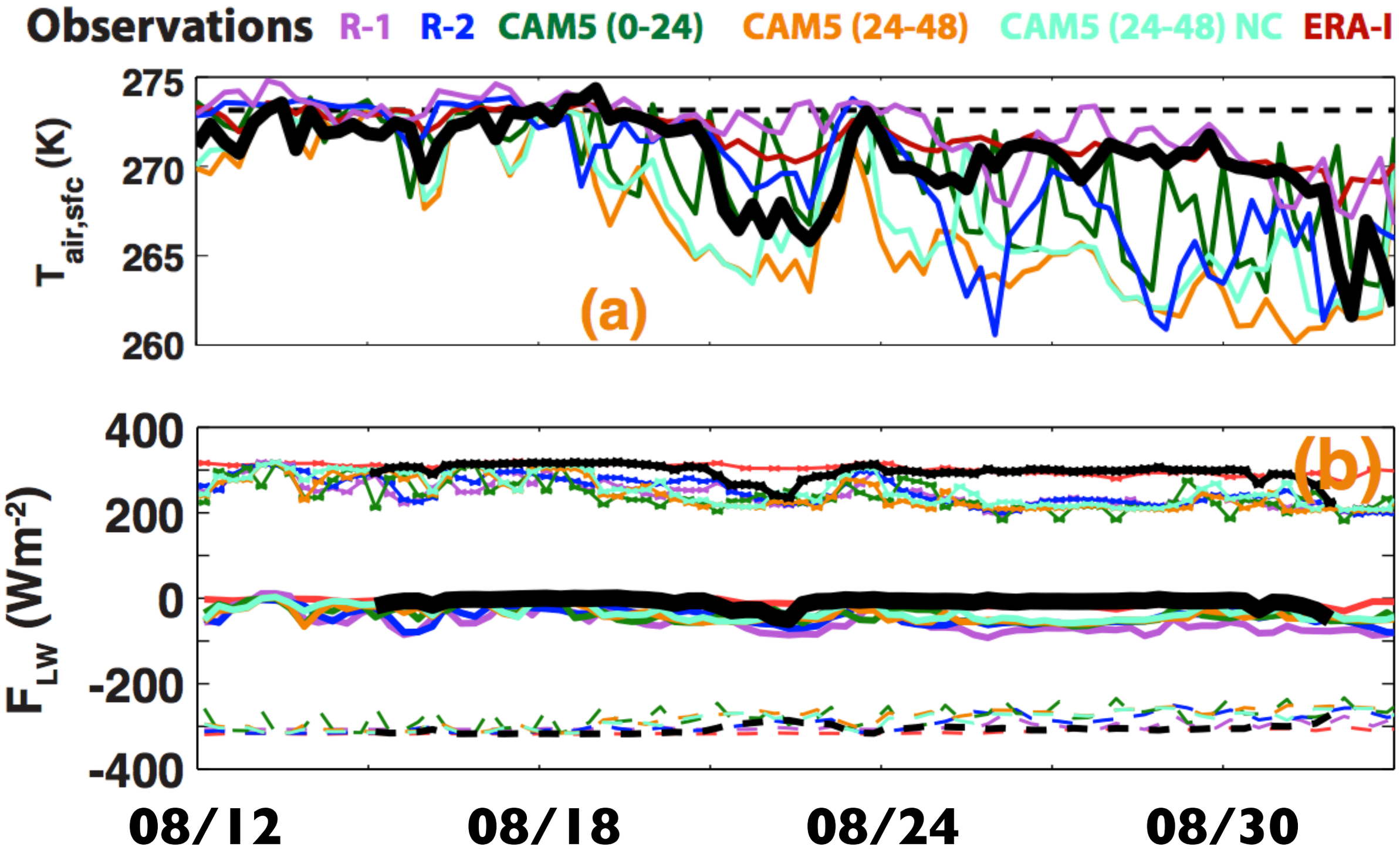


Figure from de Boer et al., (2012a)

The Role of Aerosol Properties

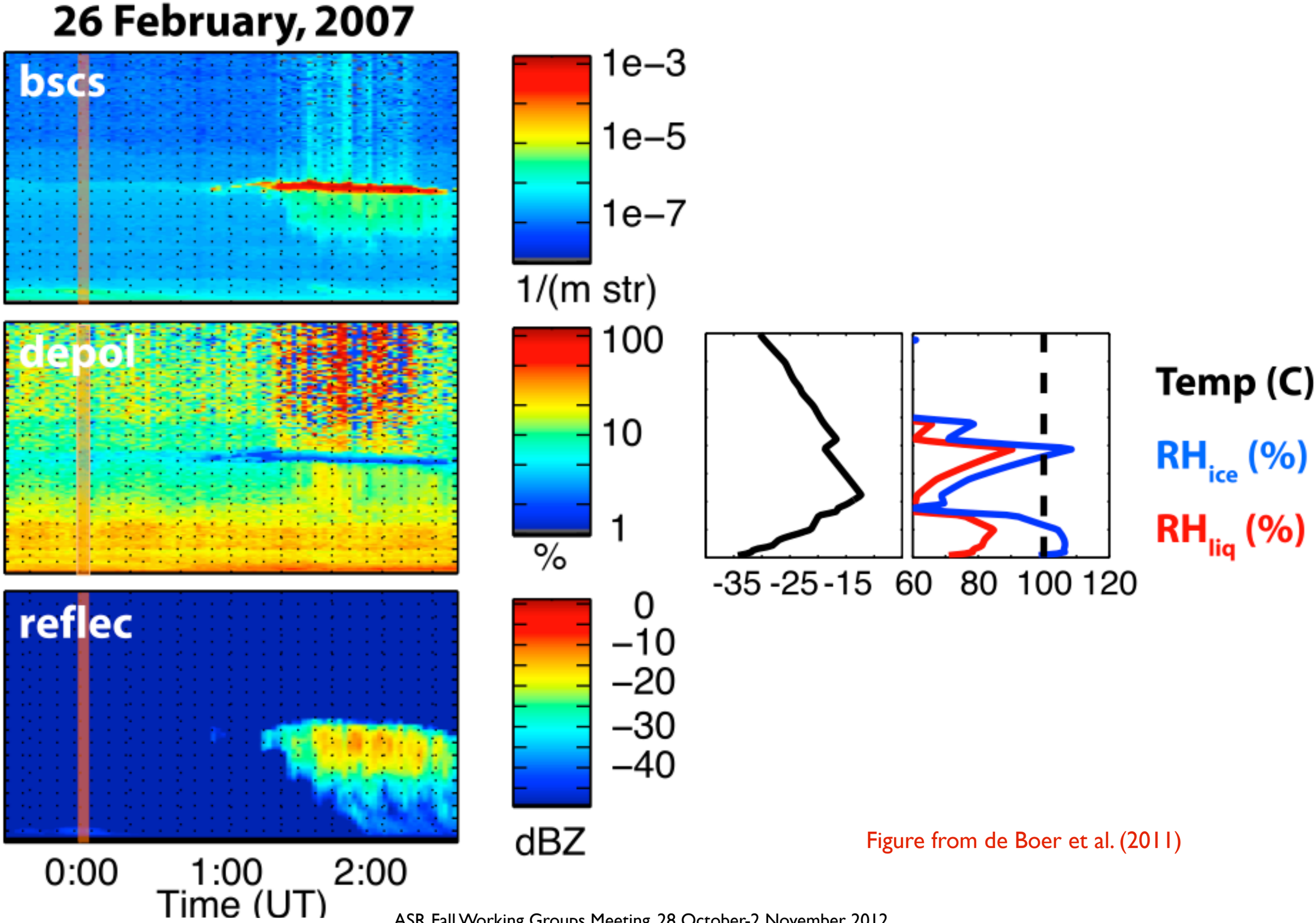


Figure from de Boer et al. (2011)

Modeling

ADD THIS DISCUSSION IN THE PREVIOUS SLIDES

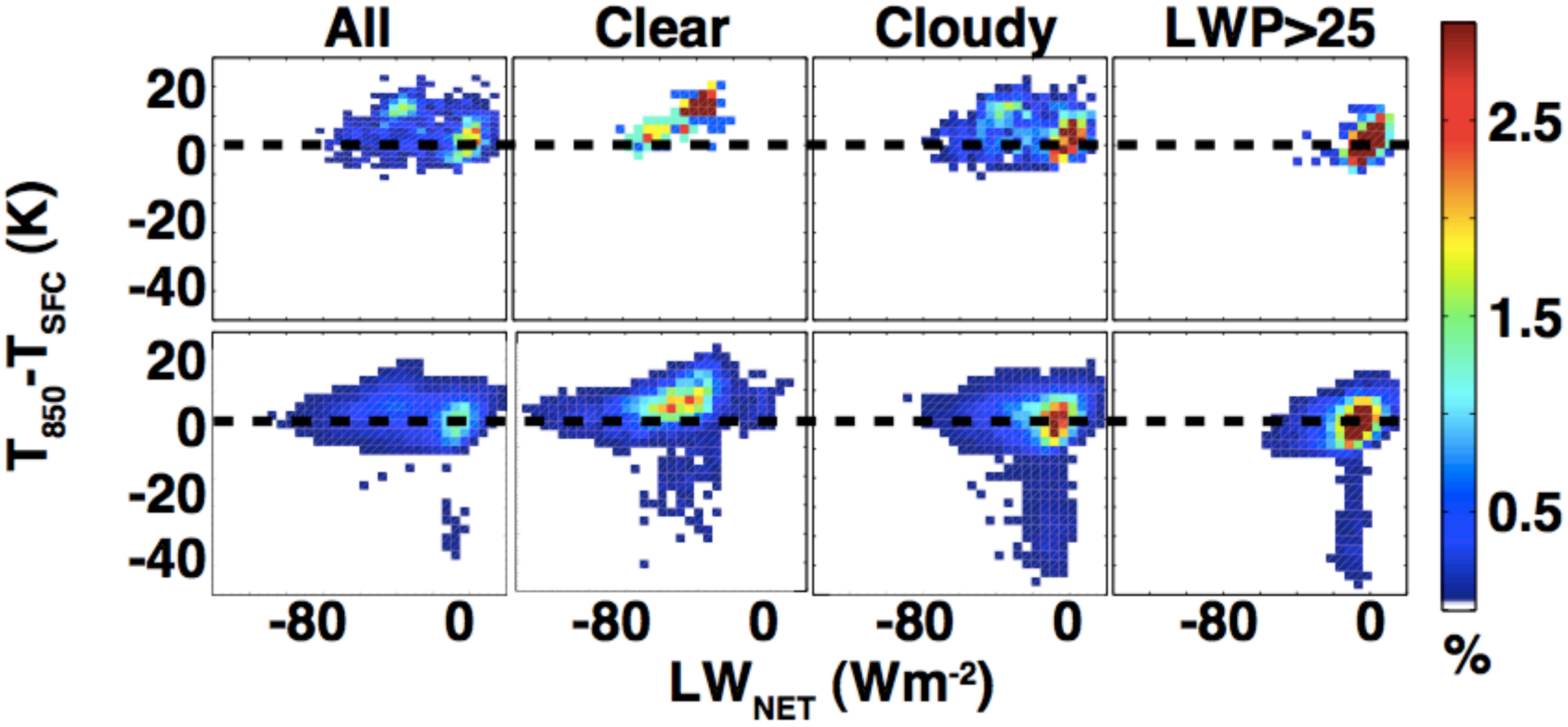
- Would our simulations look different with a revised aerosol treatment?

- What would be the impact on the spatial distribution of ice nucleation? Of aerosol transport? On ice nucleation timing (stochastic parameterizations)?

- Can we measure get long-term bulk measurements of ice nucleation efficiency by size/composition?

Influence of the Large Scale

Lower Tropospheric Stability



Open Questions

Some (limited) unanswered questions:

- Cloud droplets are generally believed to form near cloud base and grow in updrafts (Ervens et al., 2011), but ice crystals have been hypothesized to form on aerosol entrained into the cloud from above (e.g. Prenni et al., 2009; Ervens et al., 2011; Jackson et al., 2012; Fridlind et al., 2012). Are the aerosol stratified in this manner? If so, is this true at all times, or does the cloud act to cause this stratification? If not, are we missing the nucleation mechanisms responsible for mixed-phase ice?

- Can we better characterize the mode of ice nucleation for mixed-phase cloud conditions? Can we explain observed connections between droplet size distribution and ice formation (e.g. Lance et al., 2011; Hobbs and Rangno, 1985)?

- Can we come close to closing the aerosol budget? Where do the IN come from? What fraction of CCN are also capable of nucleating ice and what is the composition of the particles nucleating ice?

- Large scale influence?