Arctic Boundary Layer

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Annual Seminar 2015
Physical processes in present and future large-scale models

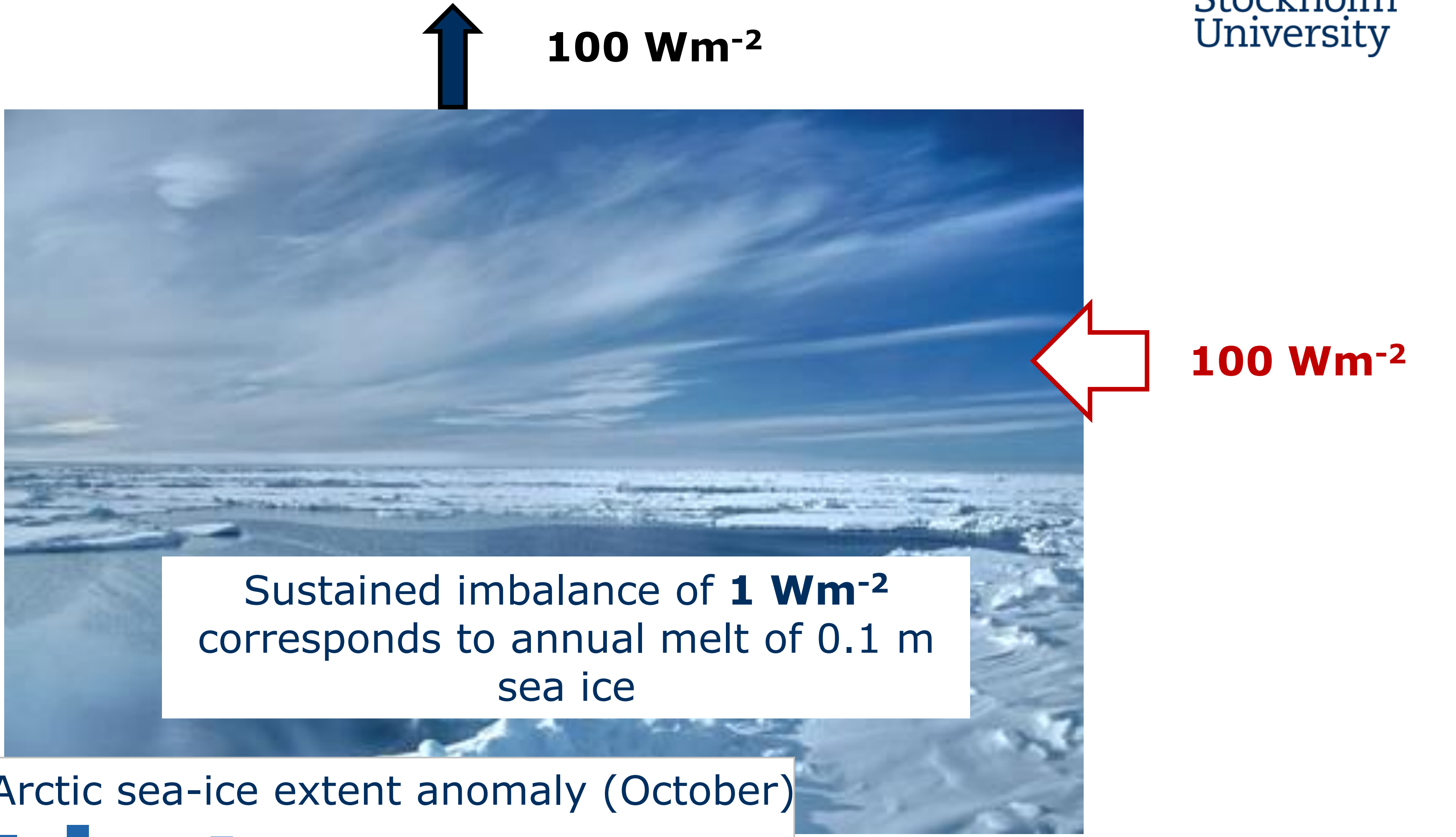
The Arctic

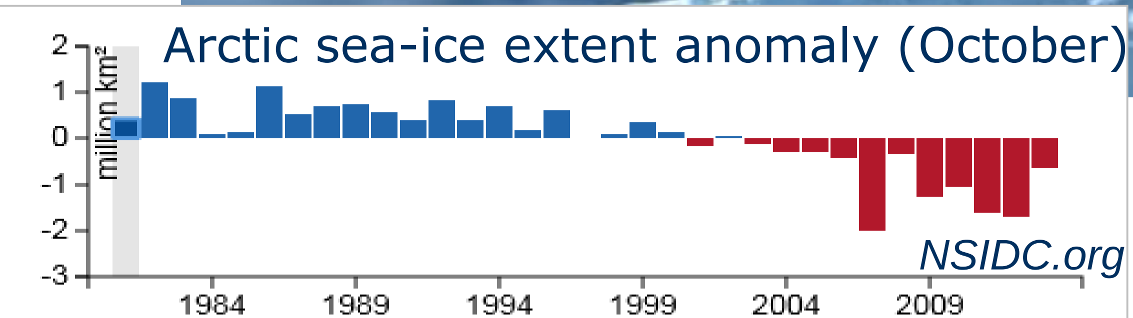
Stockholm University

Photo: Barbara Brooks

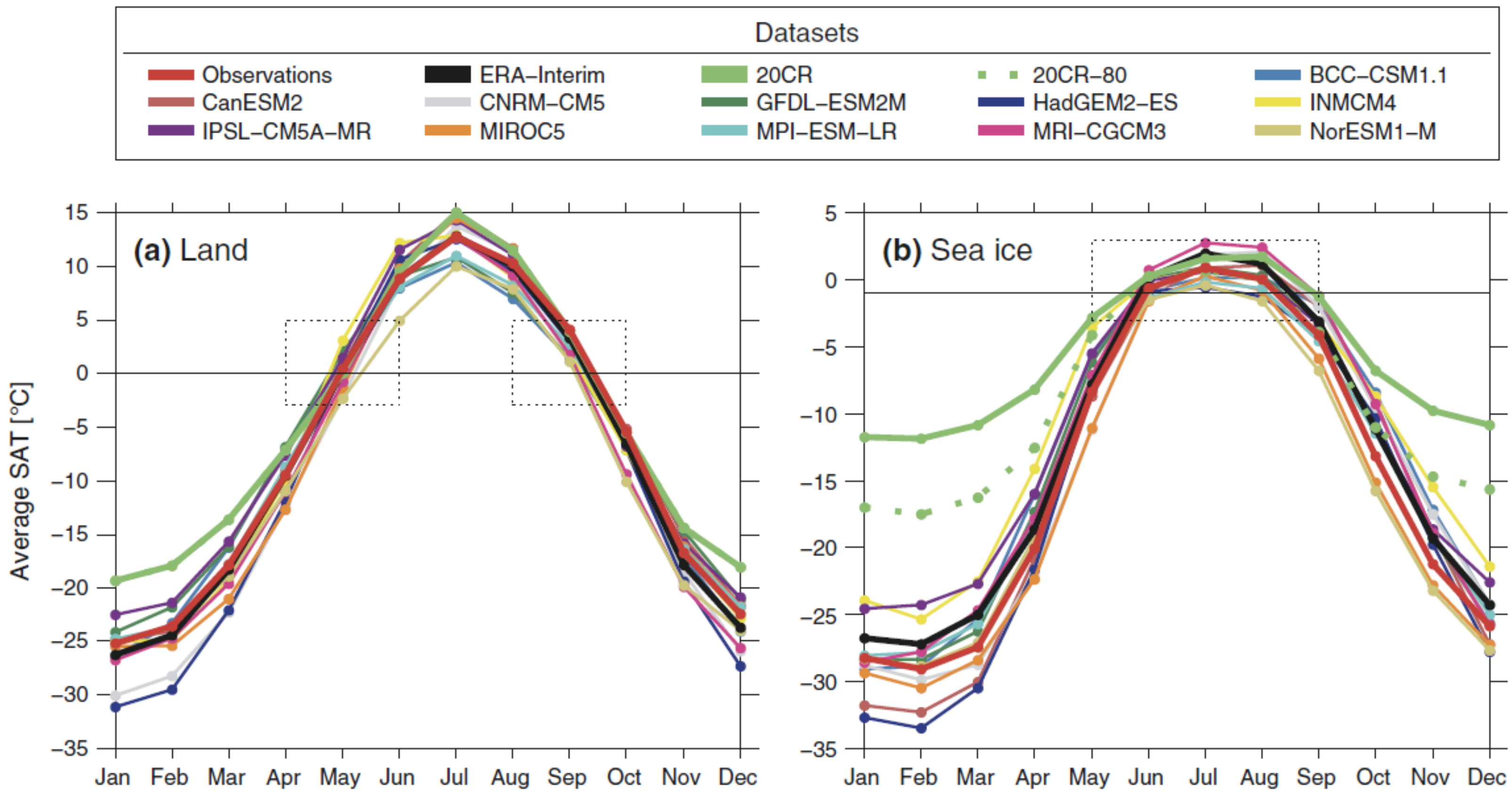
Arctic energy budget

100 Wm^{-2}





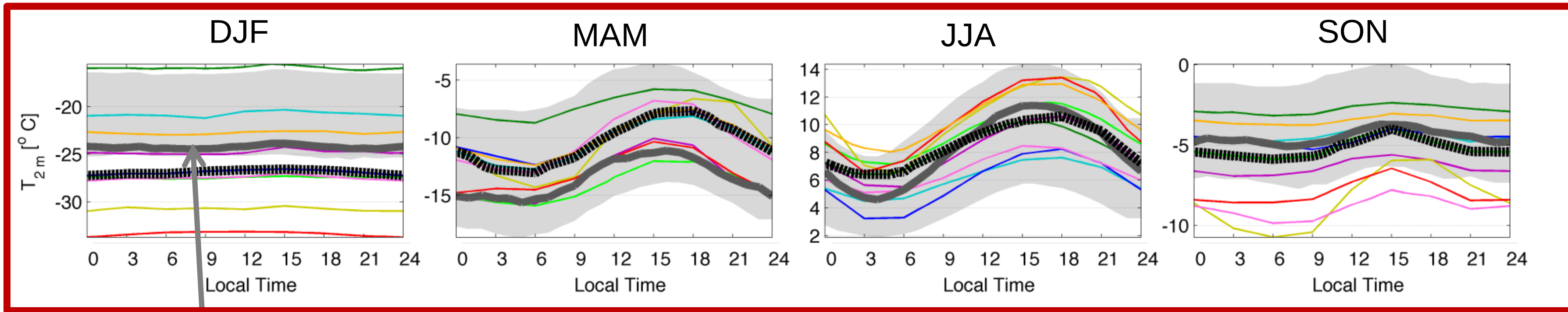
Large annual cycle …
>60 °N

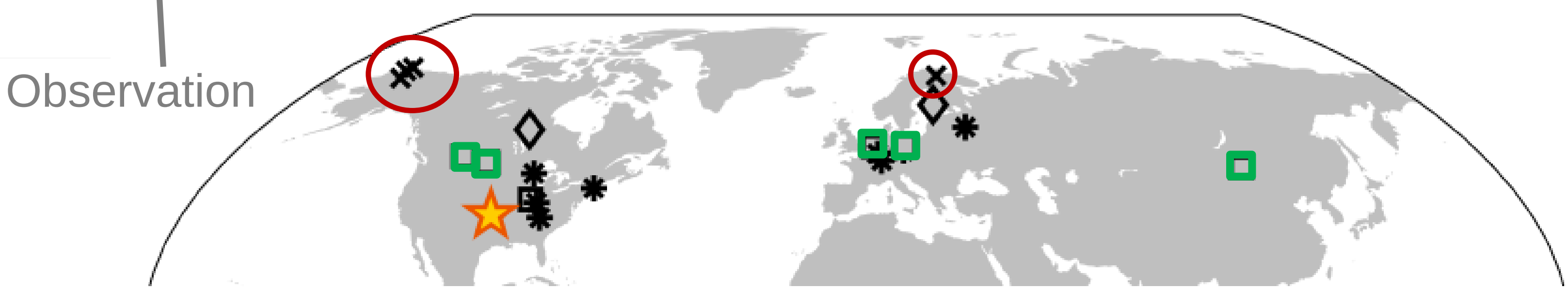


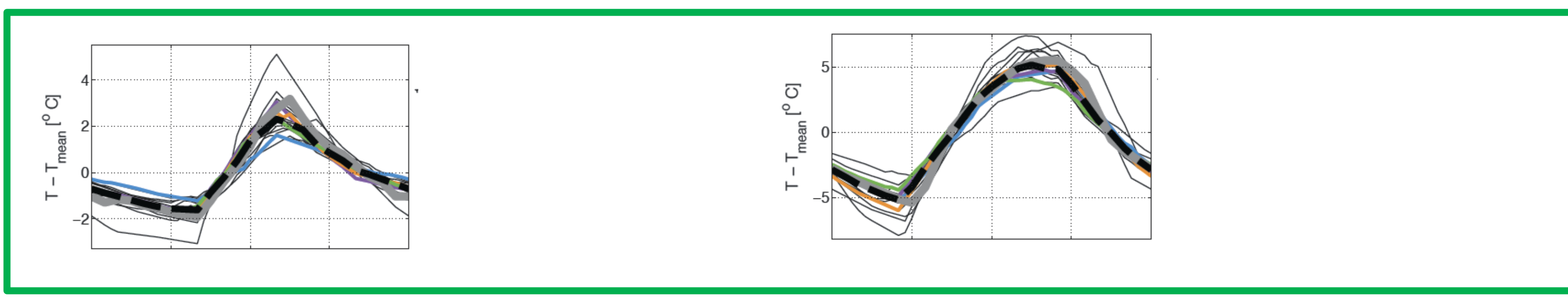
Mortin et al., 2014

... and small diurnal cycle

Flux tower observations and CMIP5 models







Svensson and Lindvall, 2015

Arctic weather

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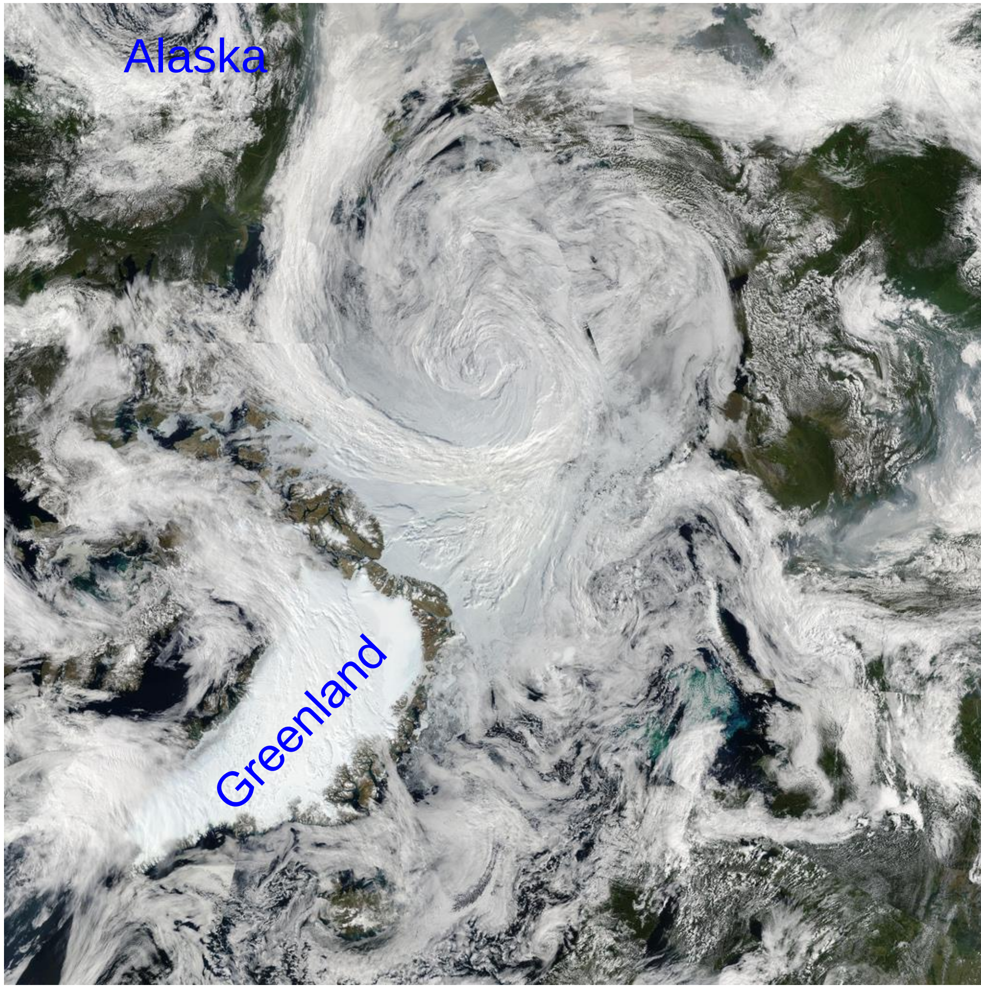
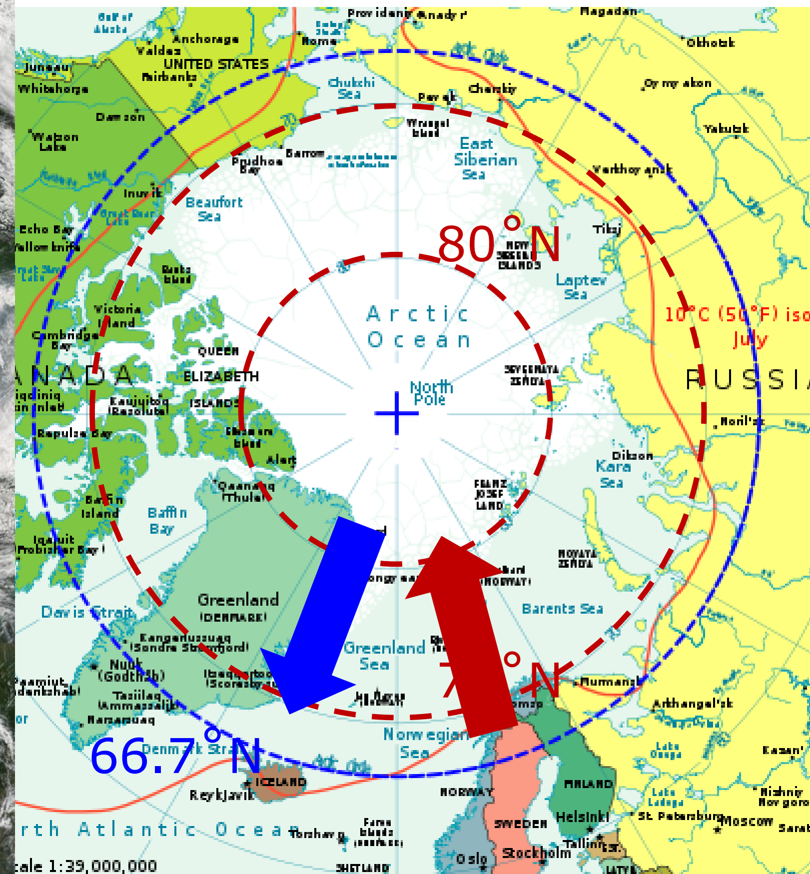
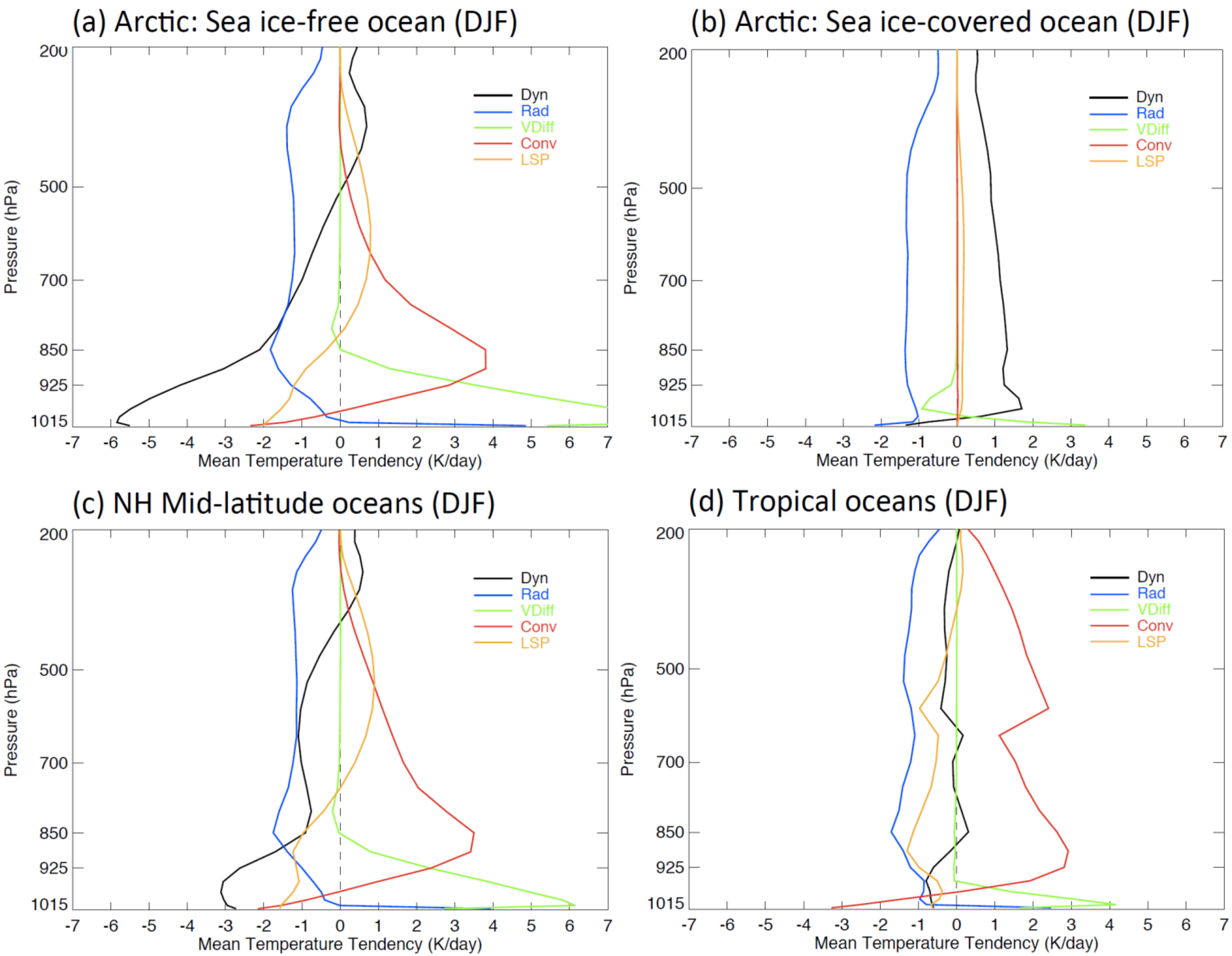




NASA/MODIS

Numerical concerns

Averaged initial tendencies of temperature (IFS)



Jung et al. 2015

Synoptic variability

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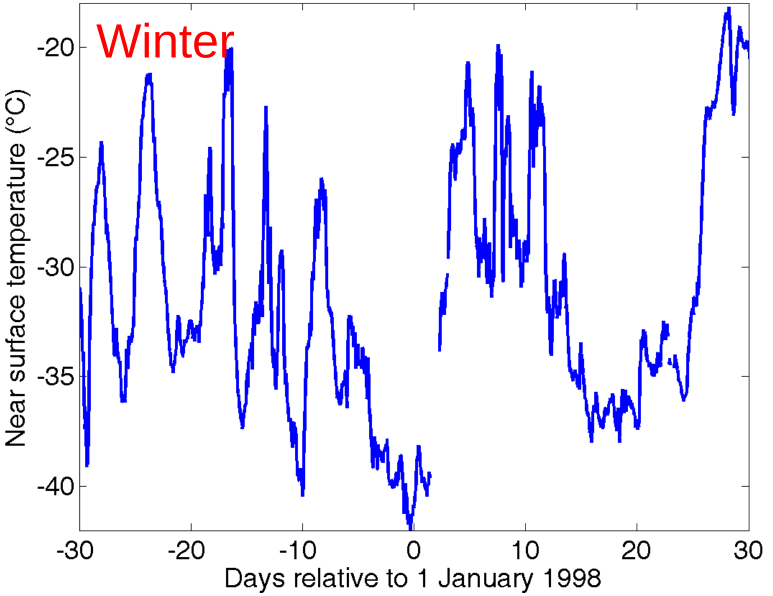
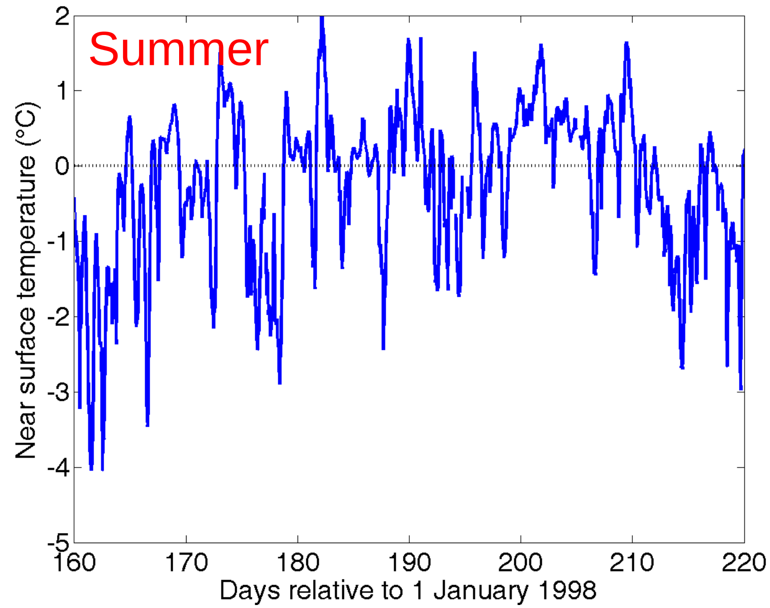
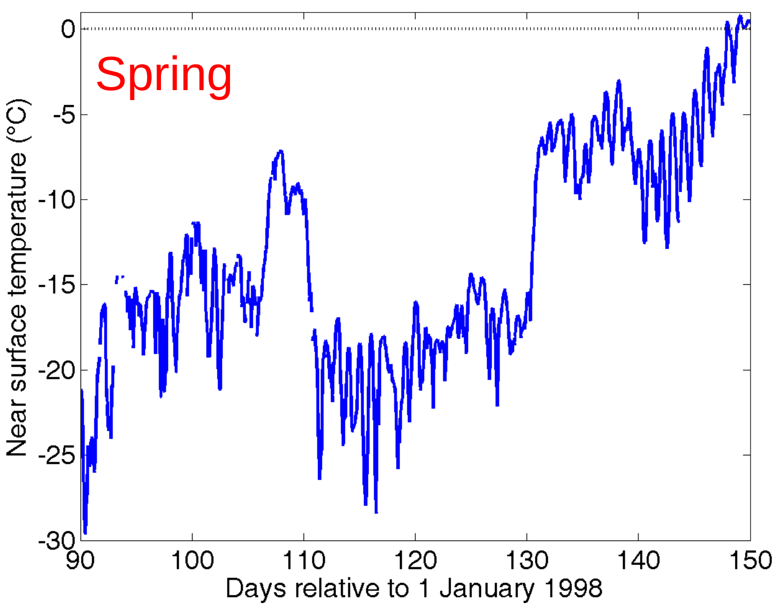
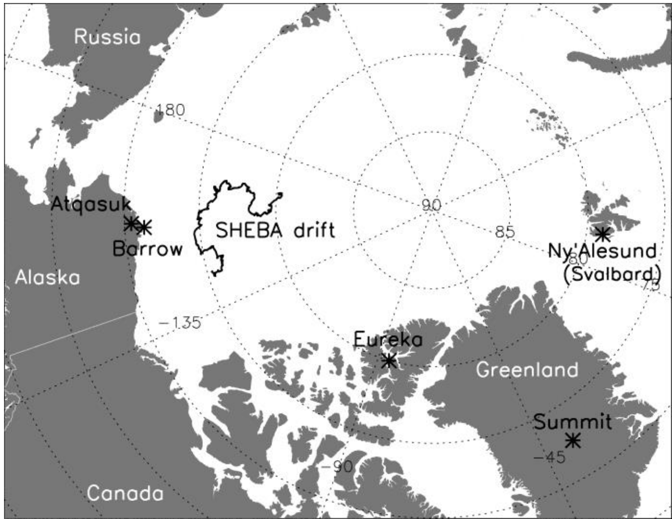
SHEBA



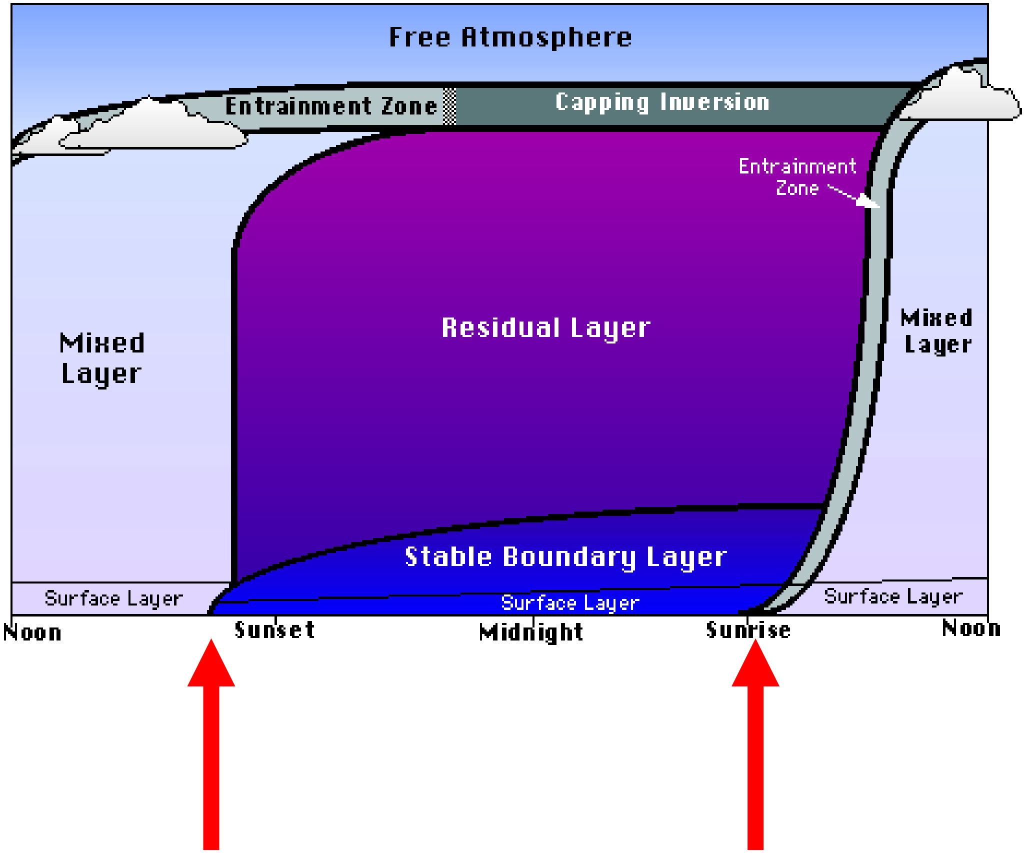


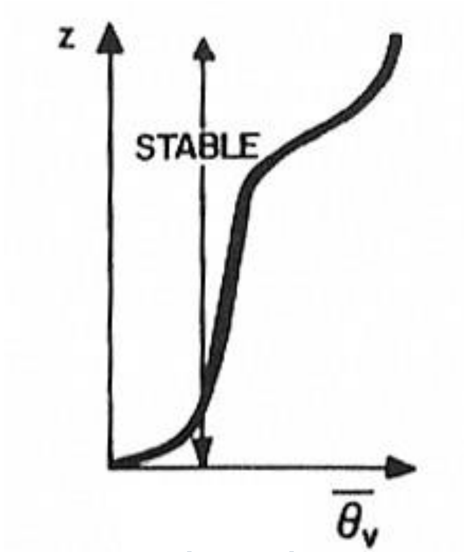
Melting ice





Stability regimes change differently…





Long-lived stably stratified PBL

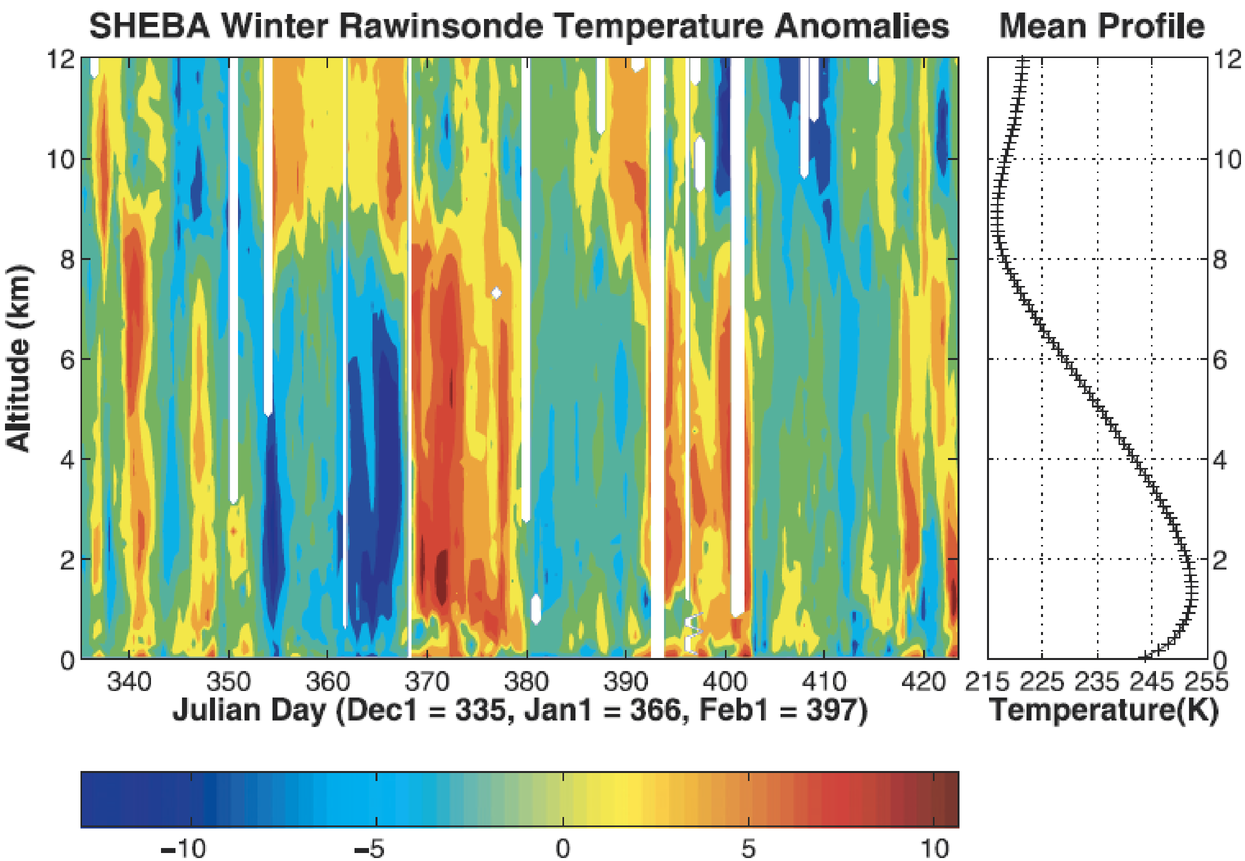
Makes it possible for gravity-waves to pass through to the surface

(see review by Sun et al., 2015)

Stable and unstable conditions are present in Arctic as well but changes are less frequent

Adapted from Stull, 1988

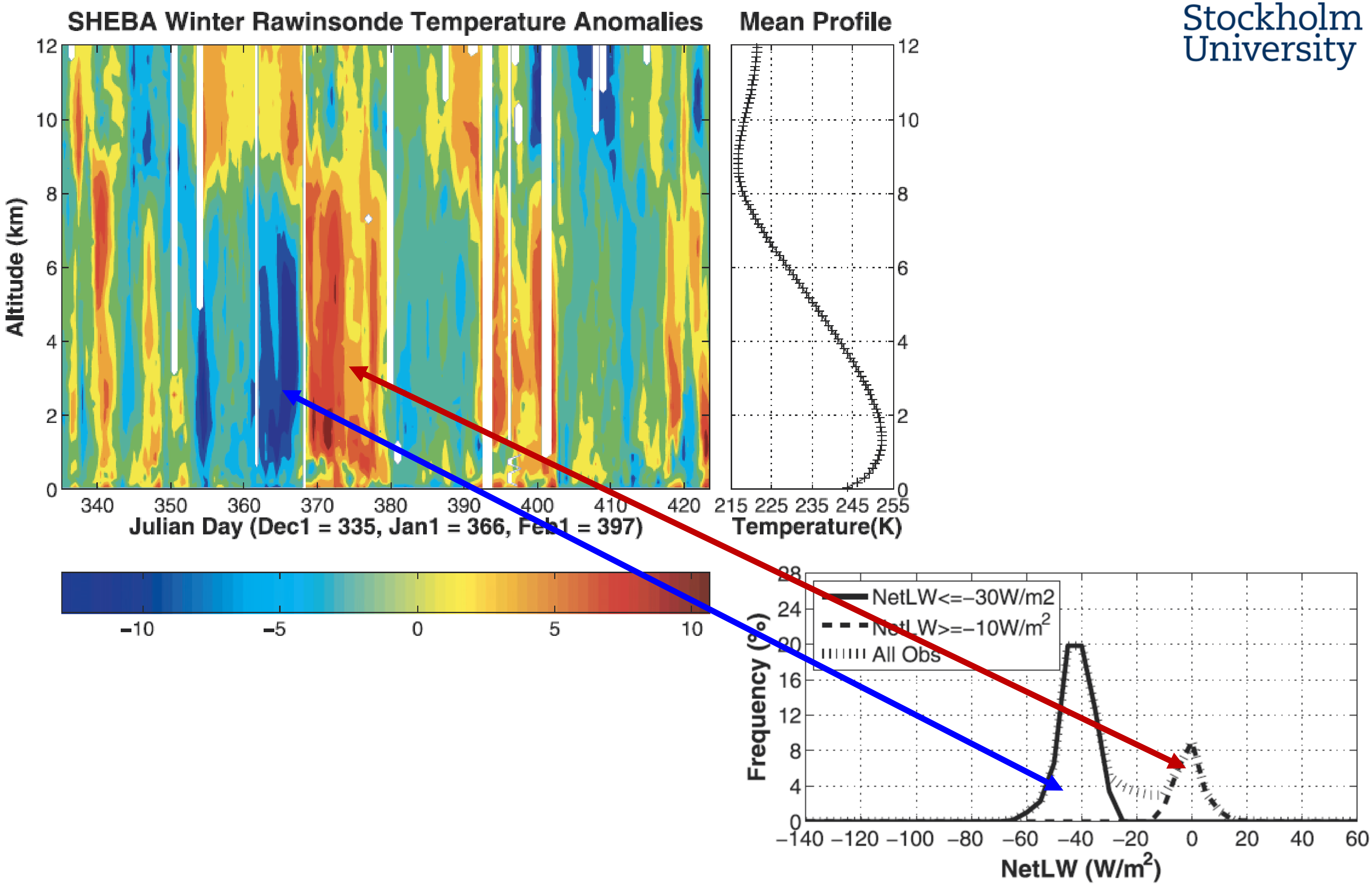
SHEBA soundings



At a particular Arctic location (SHEBA point) there are O(10) synoptic events each winter

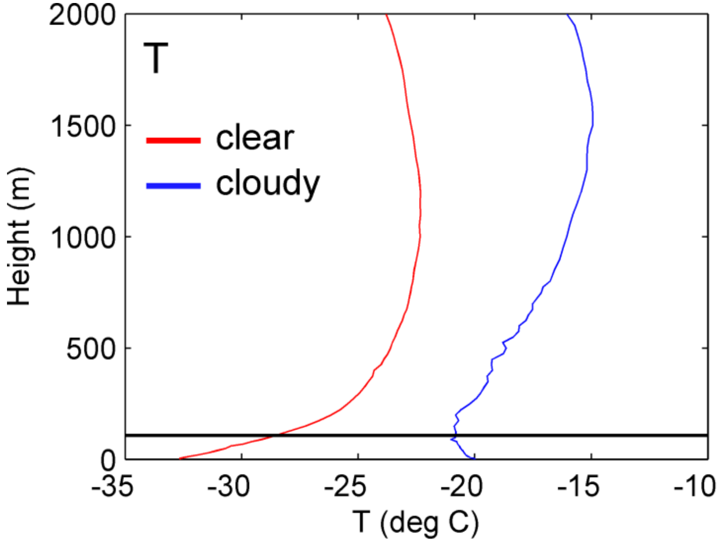
Stramler et al., 2011

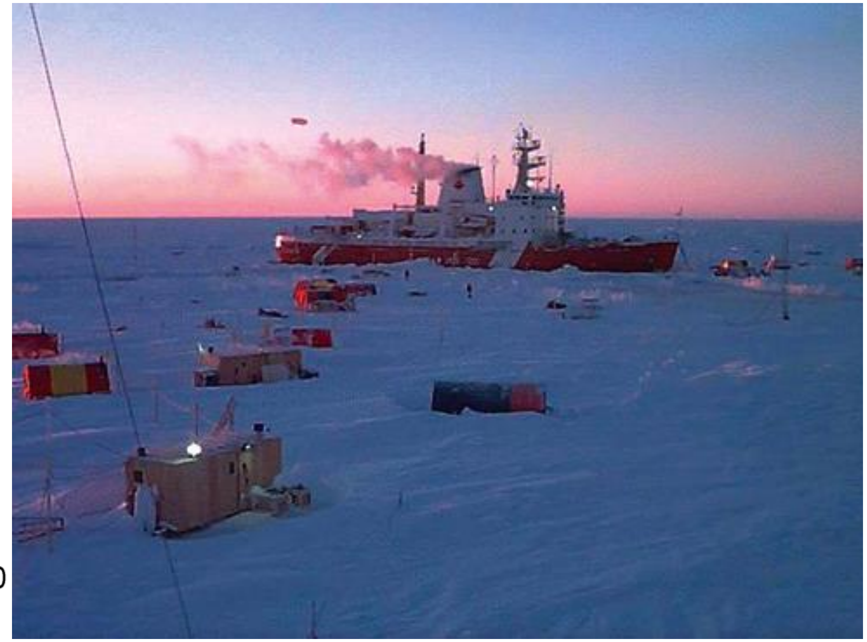
SHEBA data

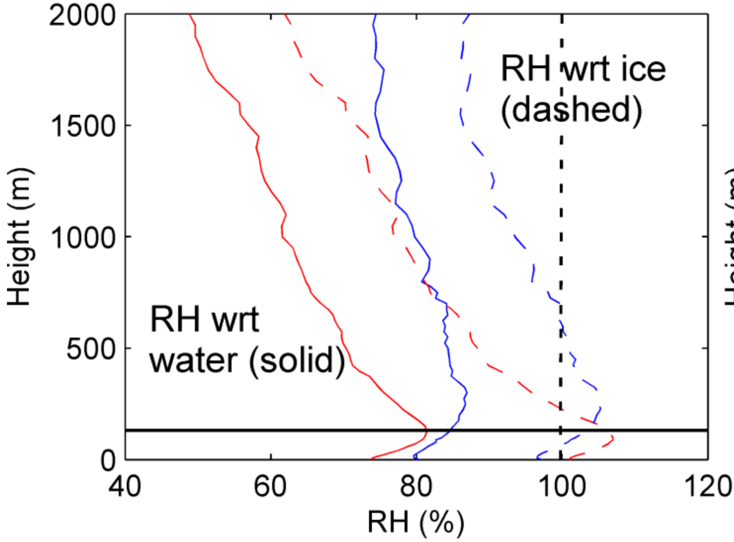


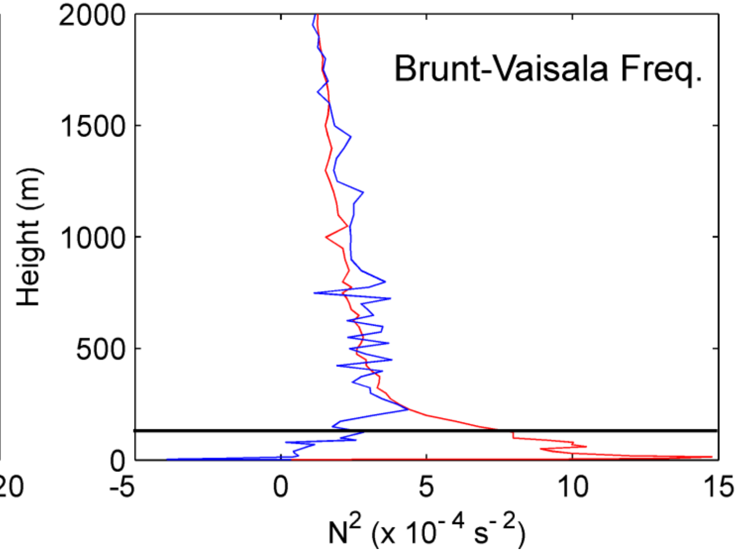
Stramler et al., 2011

Lowest layers
Mean profiles @ SHEBA









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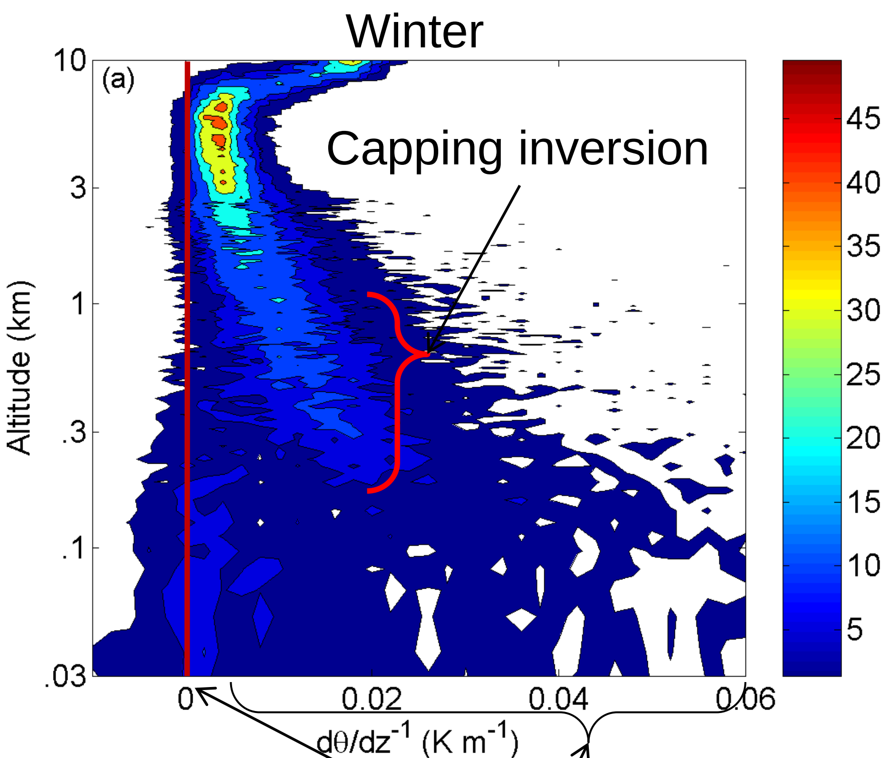
Curtesy of Ola Persson

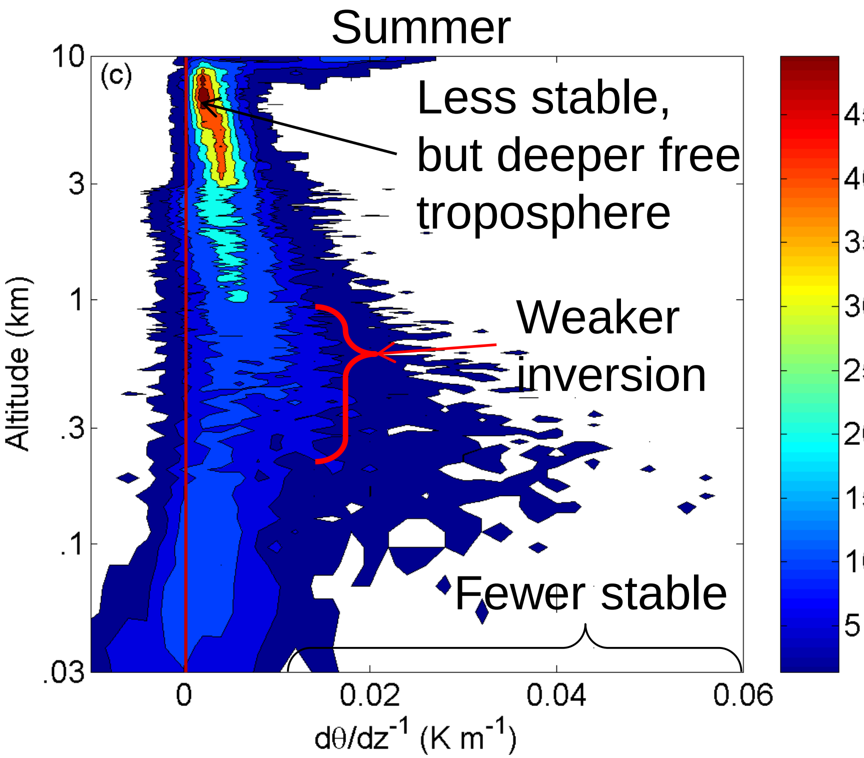
Arctic troposphere vertical structure

SHEBA



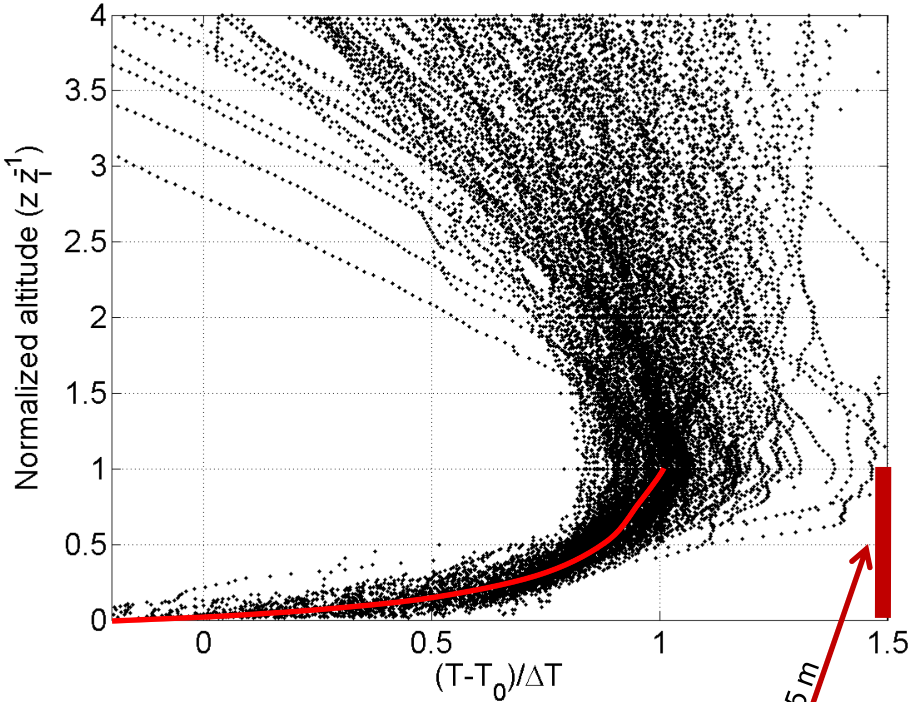
Sometimes near-neutral,…

…sometimes stable



Tjernström & Graversen 2009

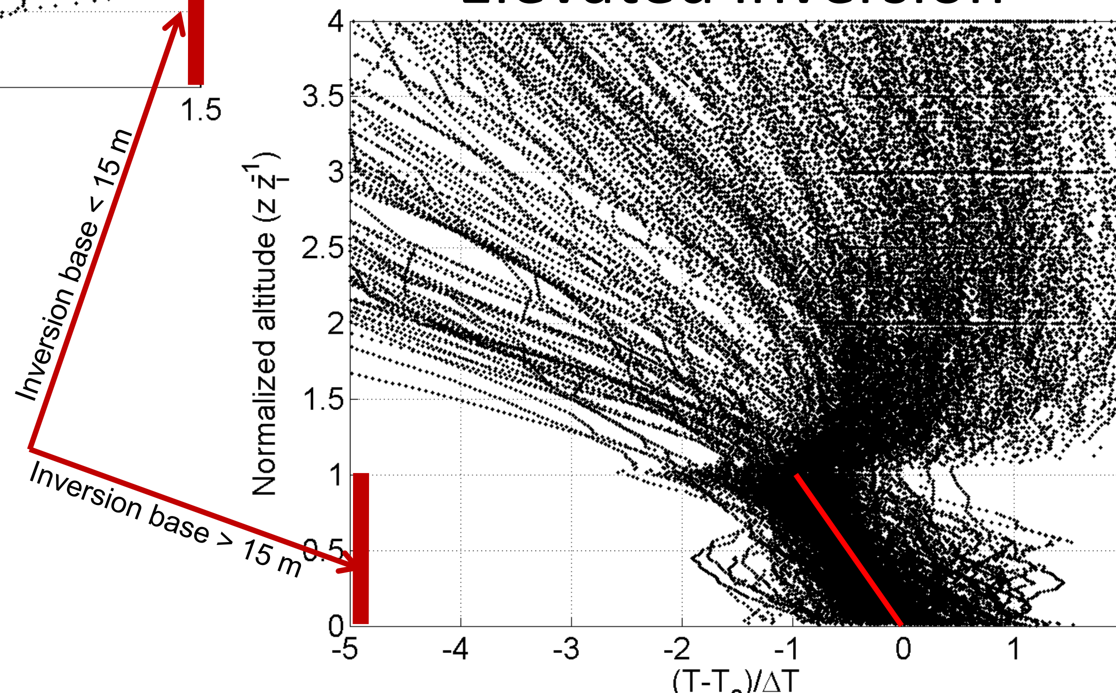
Surface inversion



Thermal structure

	Winter	Spring	Summer	Autumn
Surface	53%	15%	9%	61%
Elevated	47%	85%	91%	39%

Elevated inversion



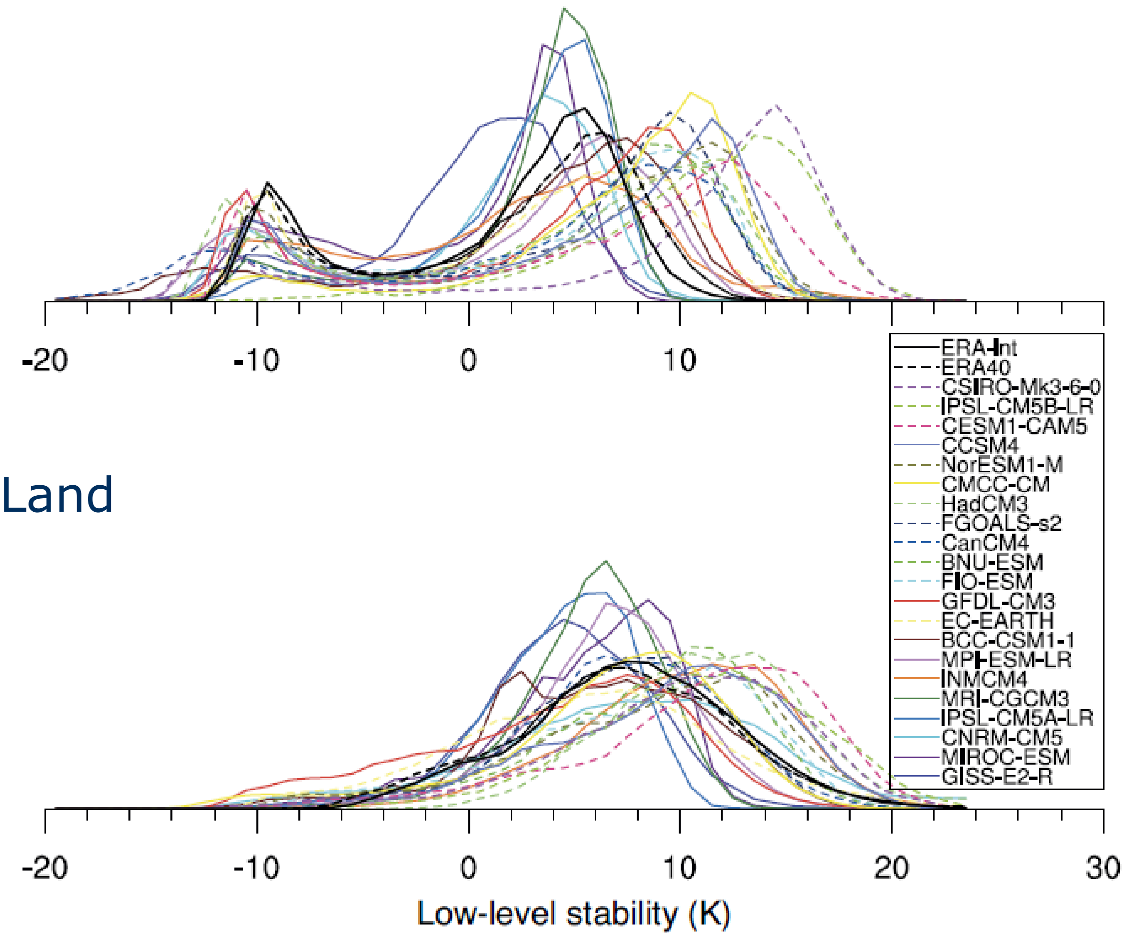
”Boundary layer”

Tjernström & Graversen 2009

Low-level stability
Winter, >64°N, CMIP5 models and ERA

Ocean

Land



T_{850hPa} - $T_{surface}$

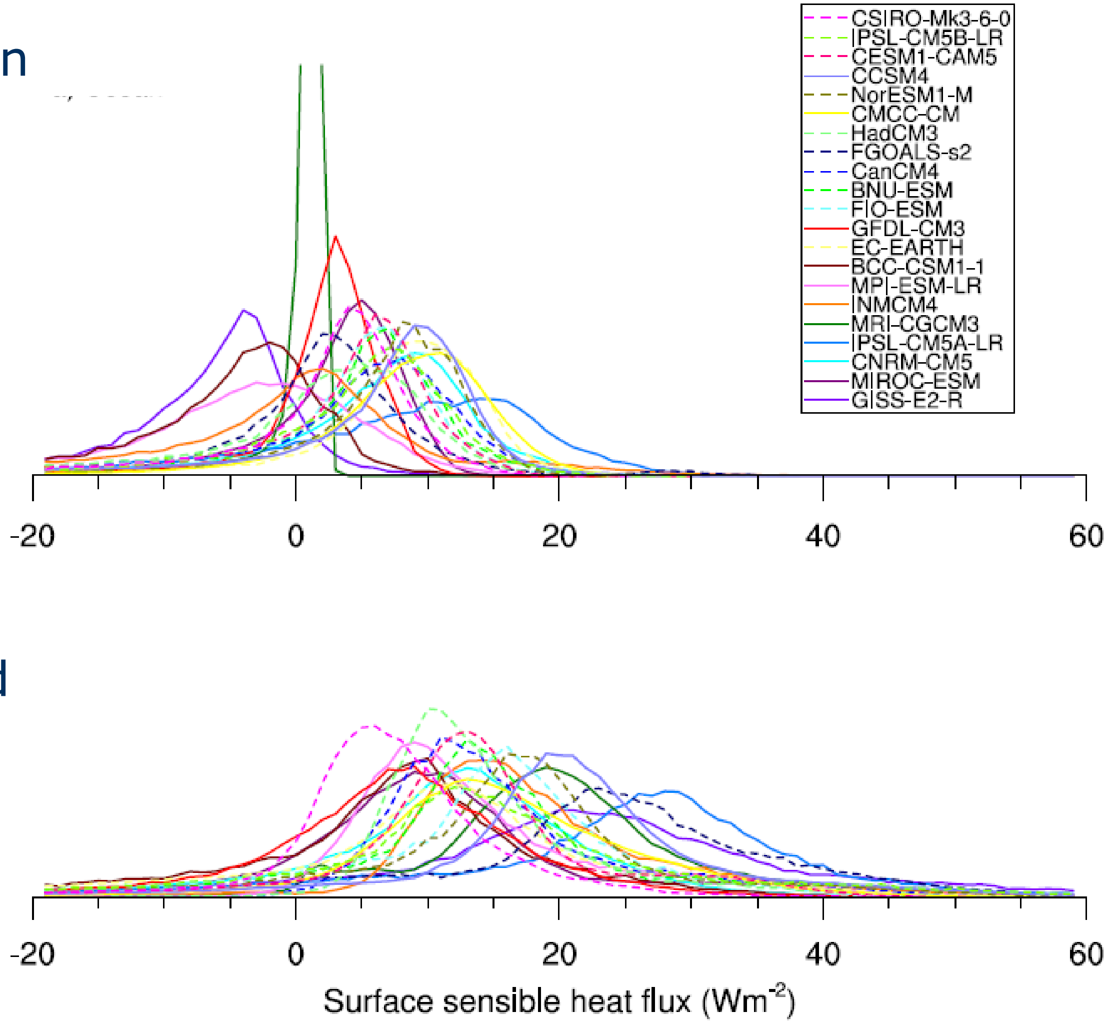
Fig. 3 PDFs of NDJF Arctic (north of 64 °N) monthly mean grid-point wise low-level stability in the historical runs, 1990-1999. Inversion strength is defined as 850 hPa temperature minus surface air temperature. The models' own land-sea masks have been used to partition data into land and ocean domains, considering any gridpoint with more than 20 percent land fraction as land. Models from Table 2 are displayed with solid lines.

Pithan et al., 2013

Surface heat fluxes
Winter, >64°N, CMIP5 models

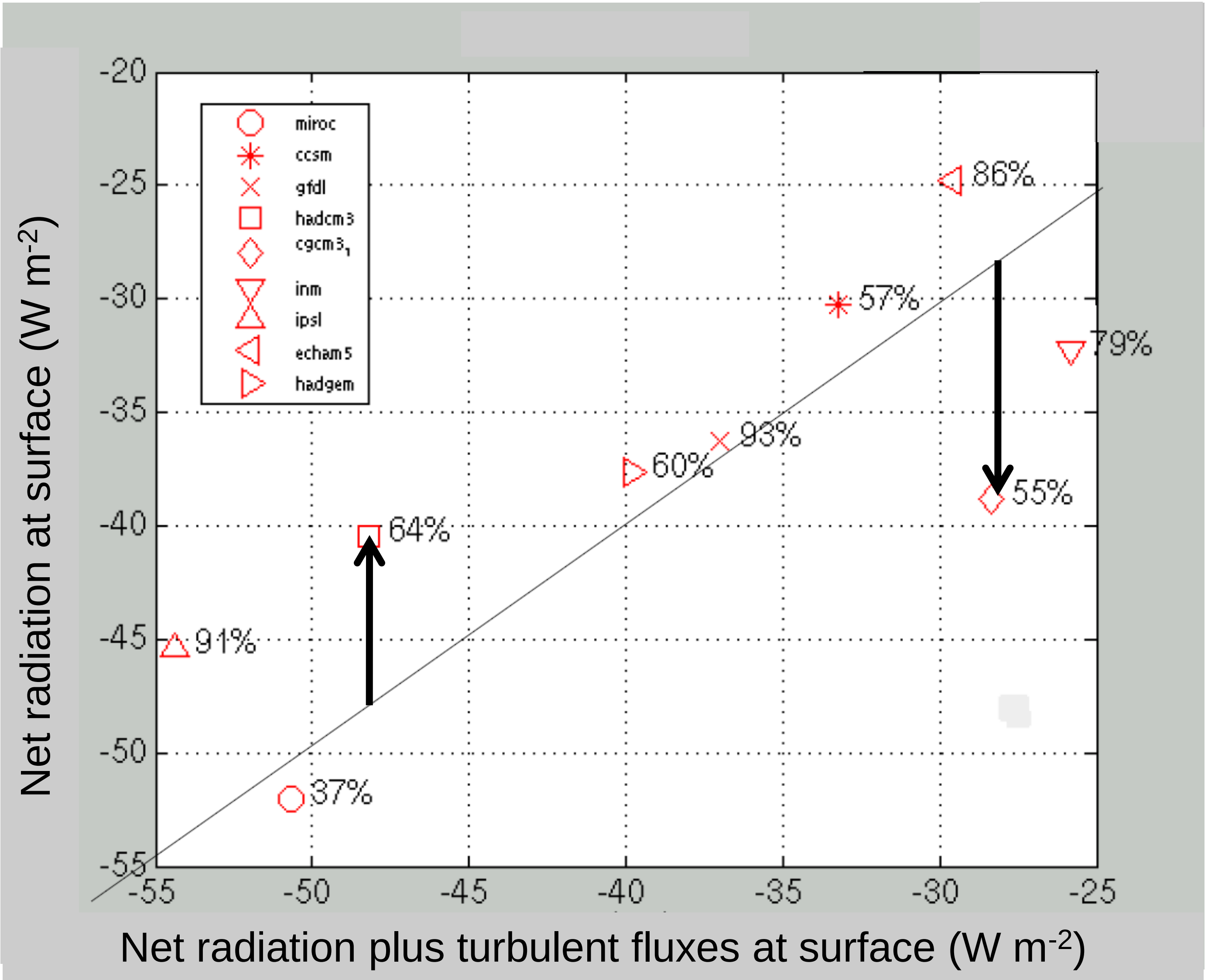
Ocean

Land



Pithan et al., 2013

Arctic surface energy fluxes



Winter (DJF) climatology

North of polar circle, only over sea-ice

Turbulent heat fluxes

Modeled surface skin temperature 239-252K

Observations 248K

Karlsson and Svensson, 2008

When clouds are present…

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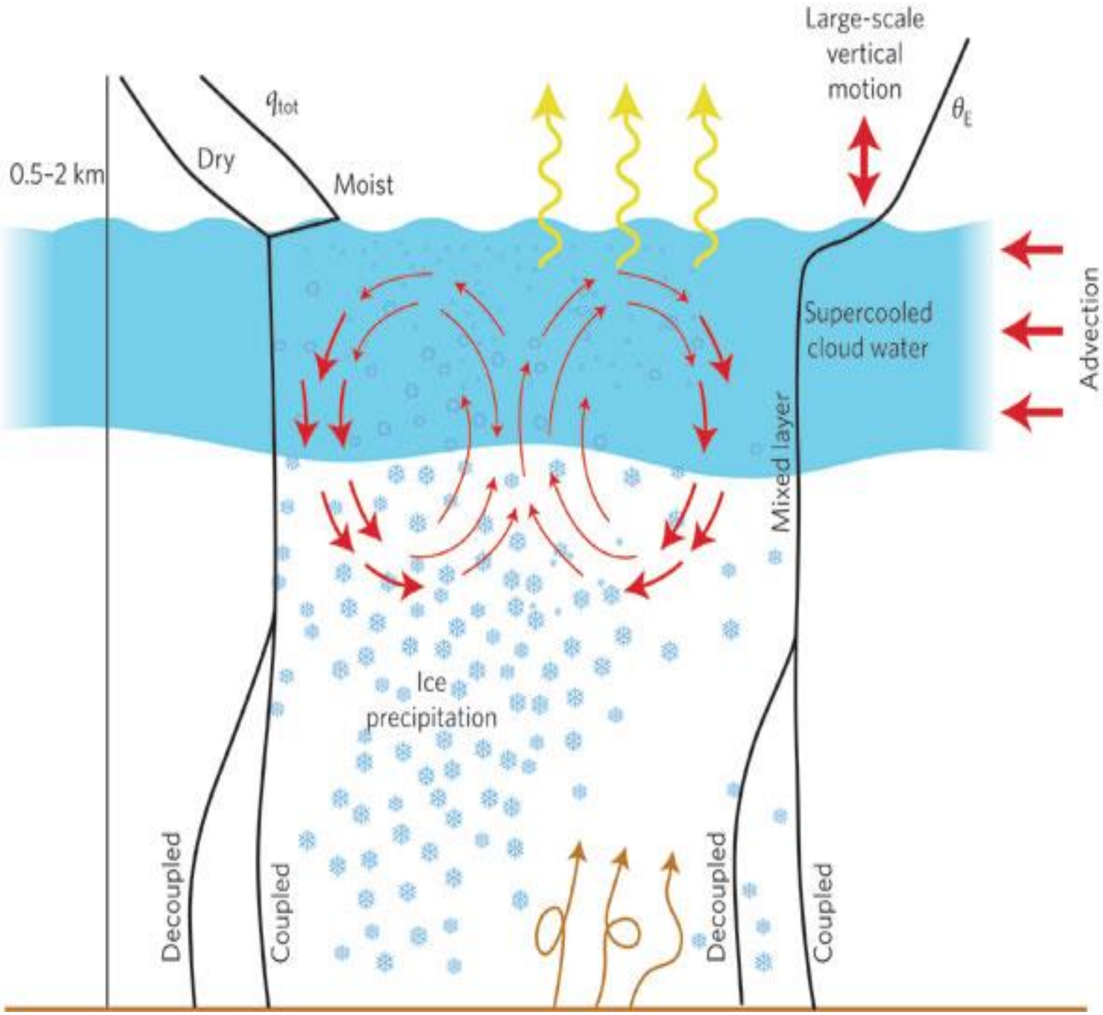

Radiative Cooling
- Drives buoyant production of turbulence
- Forces direct condensation within inversion layer
- Requires minimum amount of cloud liquid water

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

Morrison et al., 2011

Coupled and uncoupled PBLs
Dissipation rate observed during ASCOS

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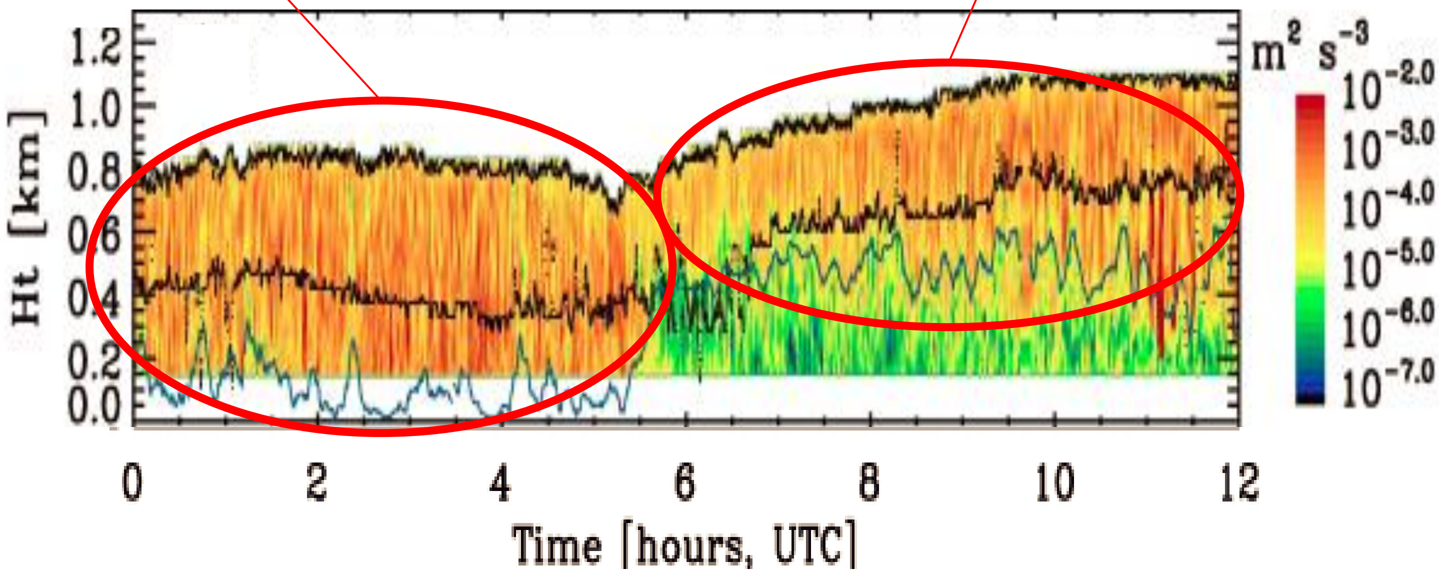
The whole layer is connected by mixing

Only the cloud layer is mixing



Courtesy Matt Shupe

Importance of the Arctic boundary layer

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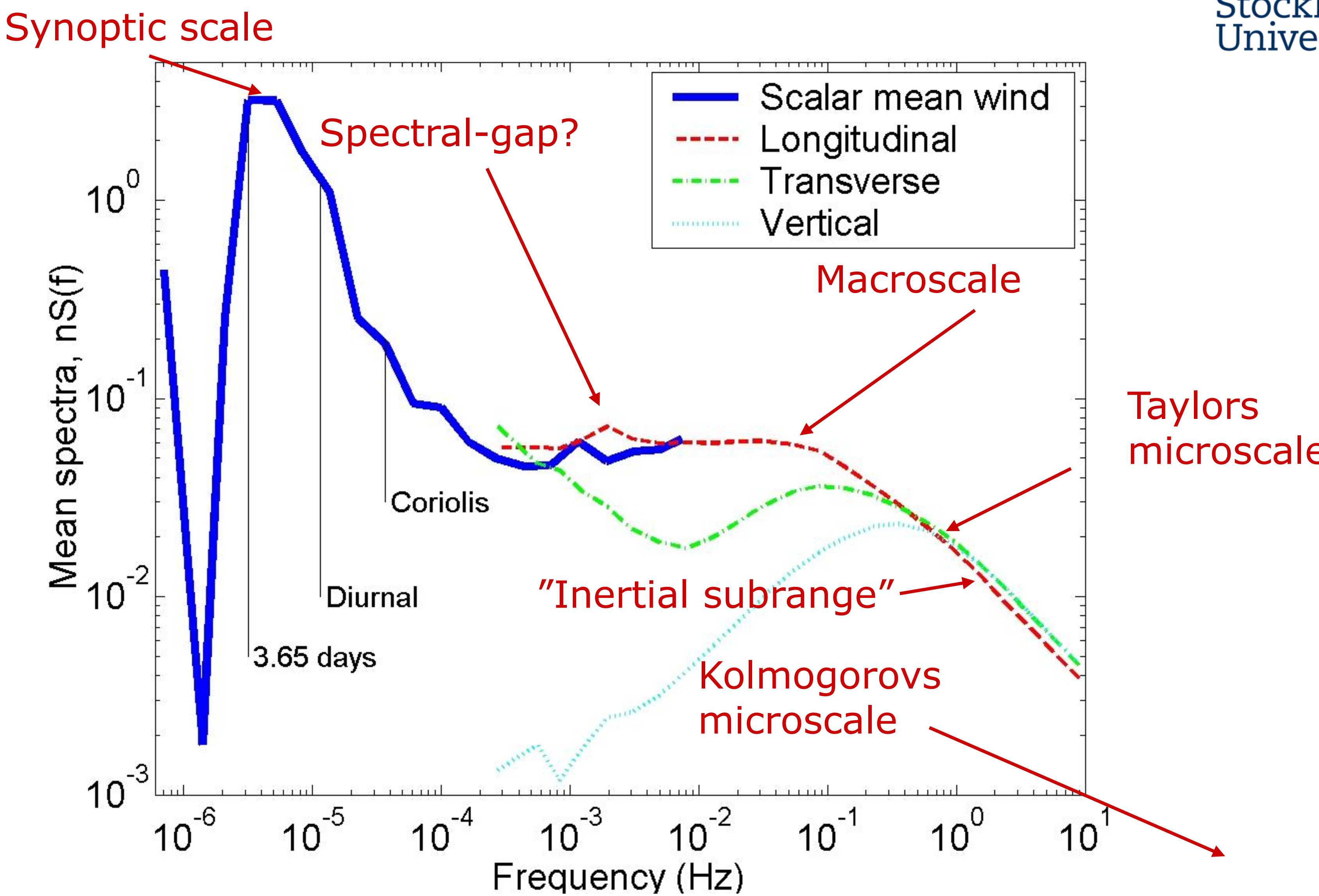
- Heat, moisture and momentum exchange between the surface and free atmosphere
- Turbulent mixing
- Turbulent fluxes are small over snow/ice – but still very important for the surface state (temperature, melt/freeze, albedo, roughness)
- Sea-ice transport and deformation

Observations from summer Arctic

AOE 2001



Courtesy M. Tjernström

In equation form …

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$$\frac{\partial U}{\partial t} + U\frac{\partial U}{\partial x} + U\frac{\partial U}{\partial y} + W\frac{\partial U}{\partial z} = fV - \frac{1}{\rho_o}\frac{\partial P}{\partial x} + \boxed{\frac{\partial}{\partial z}\left(K_M \frac{\partial U}{\partial z}\right)}$$

$$\frac{\partial V}{\partial t} + U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y} + W\frac{\partial V}{\partial z} = -fU - \frac{1}{\rho_o}\frac{\partial P}{\partial y} + \boxed{\frac{\partial}{\partial z}\left(K_M \frac{\partial V}{\partial z}\right)}$$

$$\frac{\partial W}{\partial t} + U\frac{\partial W}{\partial x} + V\frac{\partial W}{\partial y} + W\frac{\partial W}{\partial z} = g\frac{\overline{T}}{T_o} - \frac{1}{\rho_o}\frac{\partial P}{\partial z} + \boxed{\frac{\partial}{\partial z}\left(K_M \frac{\partial W}{\partial z}\right)}$$

$$\frac{\partial \overline{\Theta}}{\partial t} + U\frac{\partial \overline{\Theta}}{\partial x} + V\frac{\partial \overline{\Theta}}{\partial y} + W\frac{\partial \overline{\Theta}}{\partial z} = \boxed{\frac{\partial}{\partial z}\left(K_H \frac{\partial \overline{\Theta}}{\partial z}\right)}$$

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0$$

… where the challenge is to model the turbulent diffusivity coefficients K_m and K_h

First order closure

$$\overline{w'c'} = -K\frac{\partial C}{\partial z}$$

Turbulent flux

$$K = \left|\frac{\partial U}{\partial z}\right| l^2 F_{m,h}(Ri)$$

$$l : length\ \ scale$$

Diffusivity K depends on characteristics of turbulent flow

$$Ri = \frac{g}{\theta}\frac{\partial \theta}{\partial z} \Bigg/ \left|\frac{\partial U}{\partial z}\right|^2$$

Richardson number
(measure for local stability)

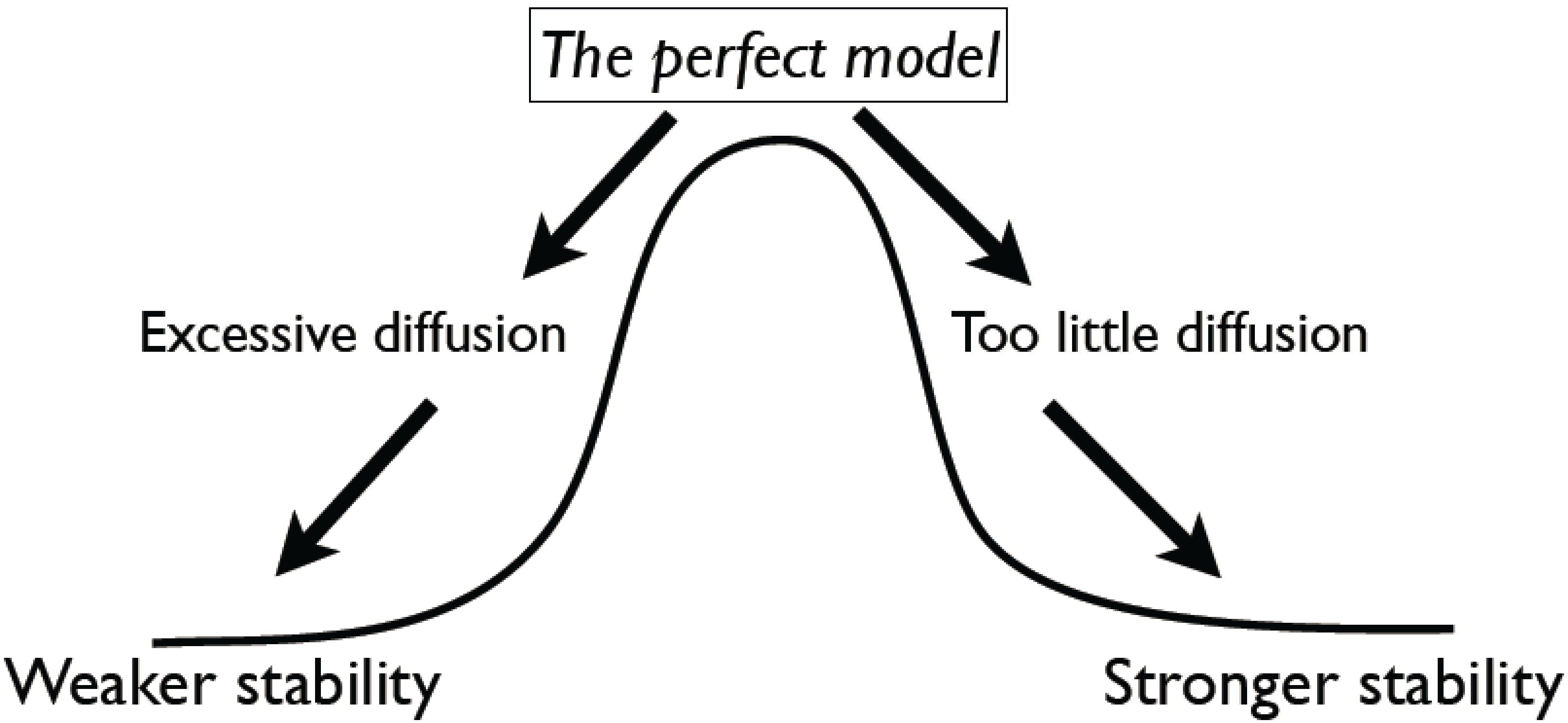
Higher-order closure models

These models are mostly based on work by Mellor-Yamada and may have:

- Prognostic equations for the turbulent kinetic energy (prescribed lenght-scale, in combination with prognositic equations of length scale or dissipation or ...)
- Prognostic equations for the total turbulent energy – kinetic and potential
- Explicit algebraic Reynold Stress and Normal Quasi-Normal Scale Elimination

The models may have a theoretical critical Ri number or not …

Properties of the stable boundary layer



Too high surface winds, too large surface heat fluxes and no LLJ

Danger of run-away cooling, usually not happening, saved by shear, radiation or conductivity

Stable boundary layer mixing

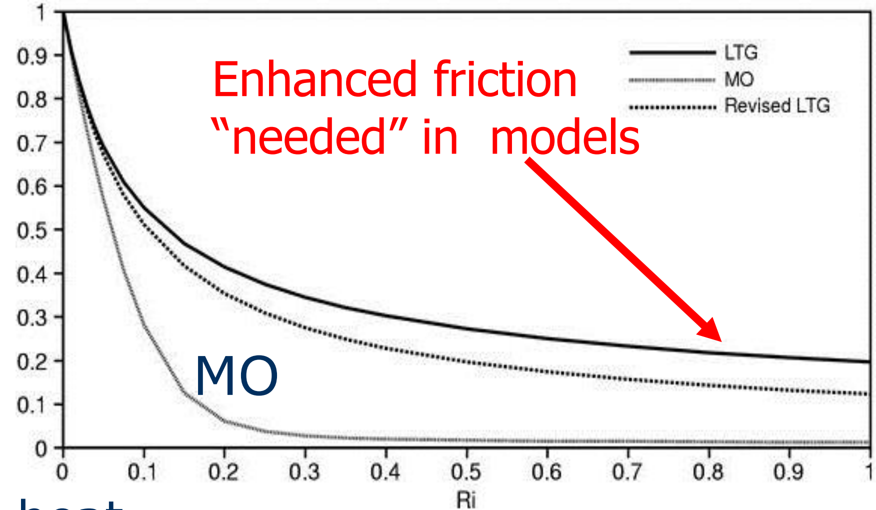
Stockholms universitet

NWP models
need a long tail
formulation to get the
synoptic scale right
(Louis et al. 1982)

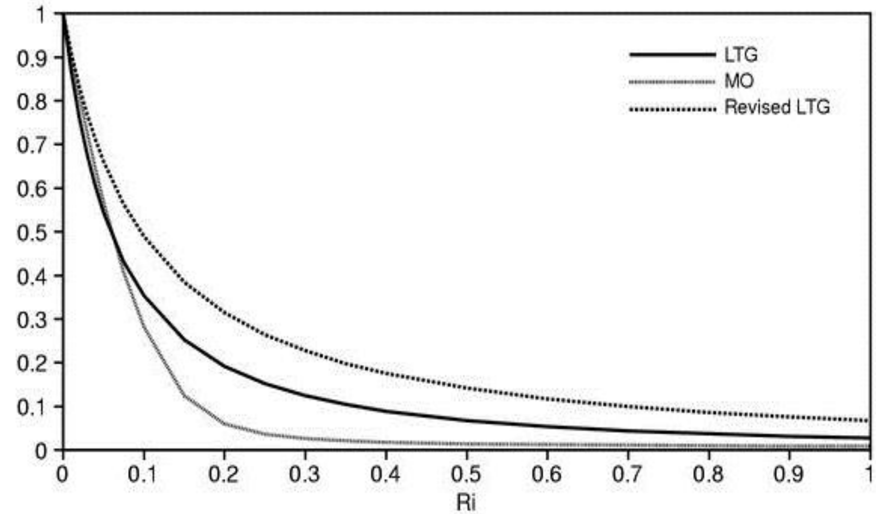
Observations follow the M-O type of functions
(Beljaars and Holtslag, 1991)

By changing this functions
you can easily change the
modeled temperature
significantly

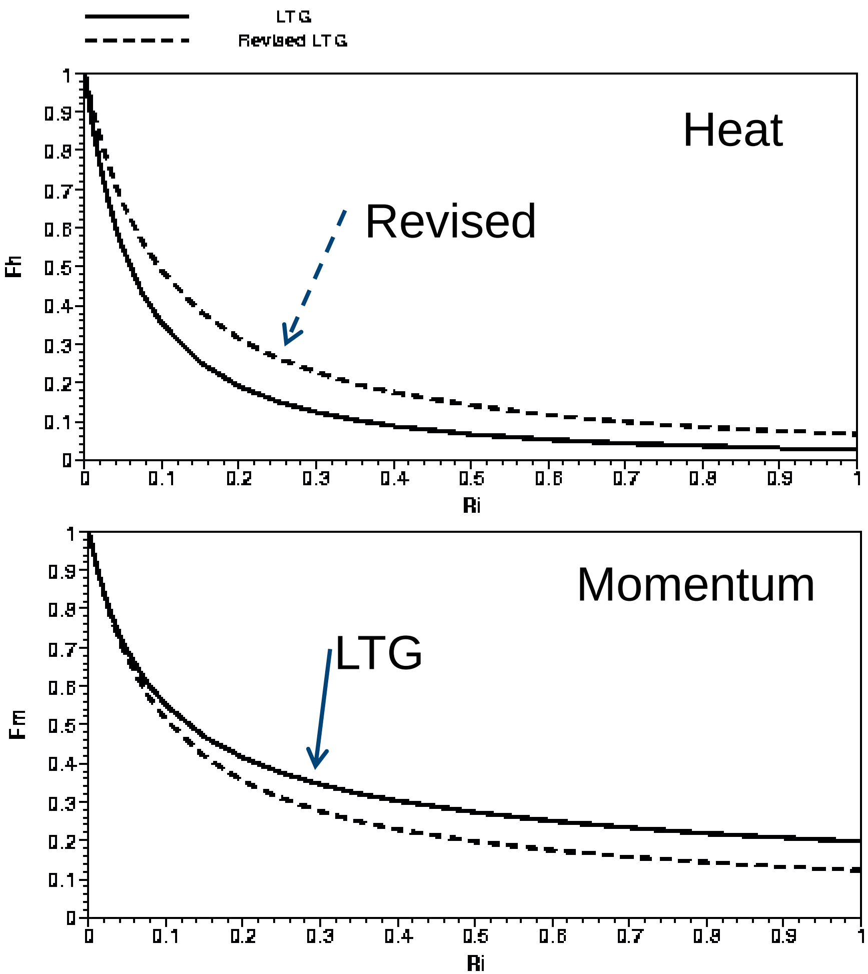
Stability functions for momentum

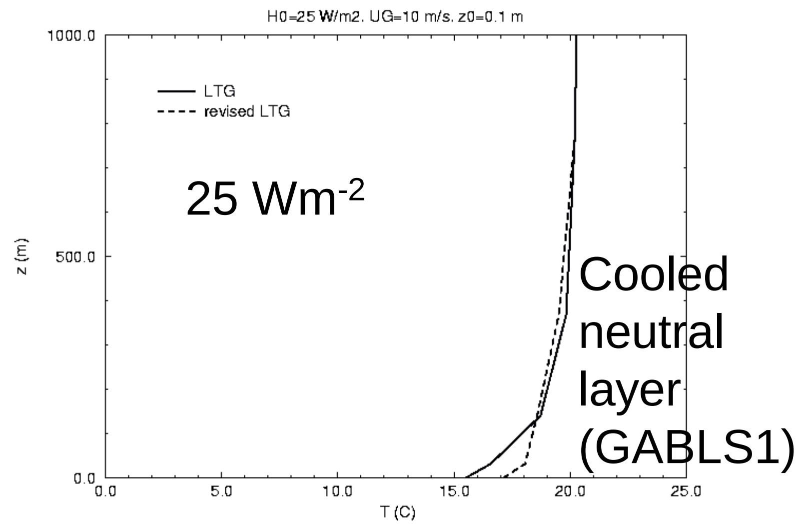


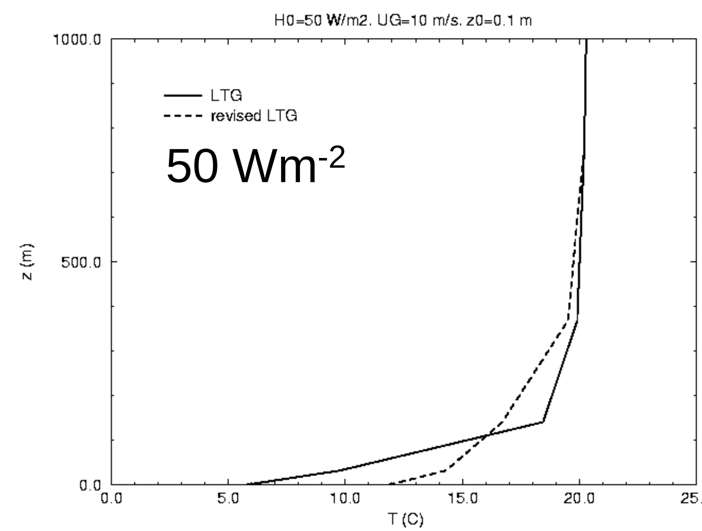
and heat



ECMWF IFS



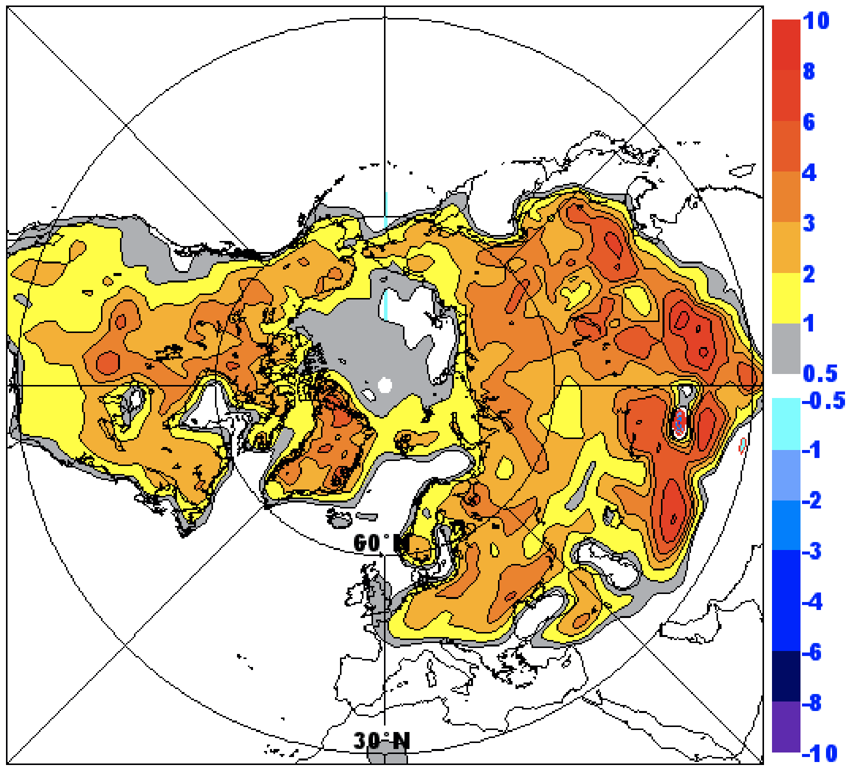




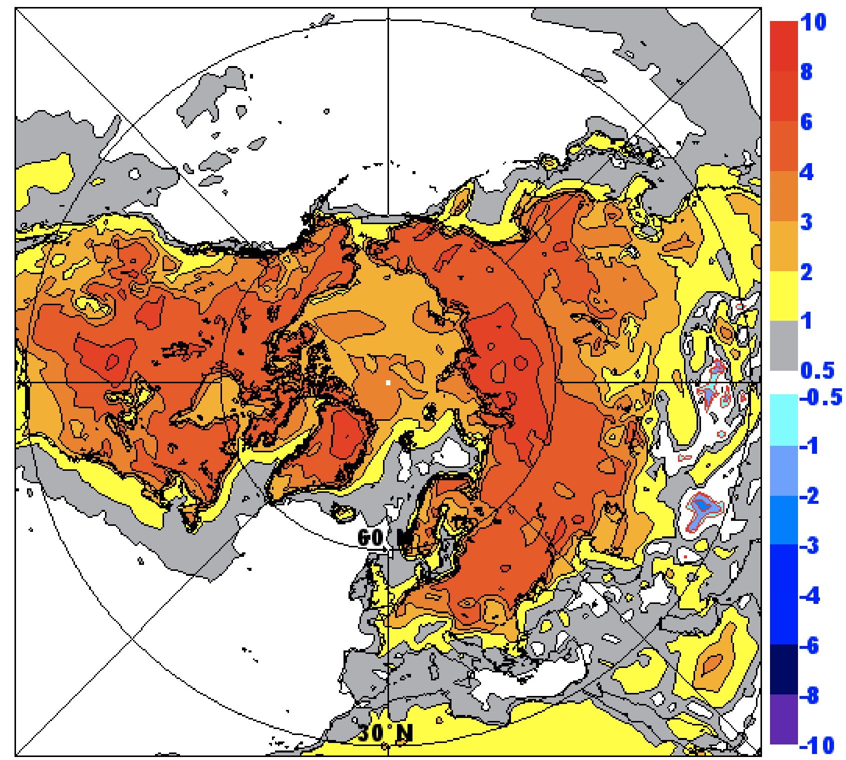
Courtesy A. Beljaars

Difference in 2m temperature for January 1996

Effect of revised LTG in 1994 model version



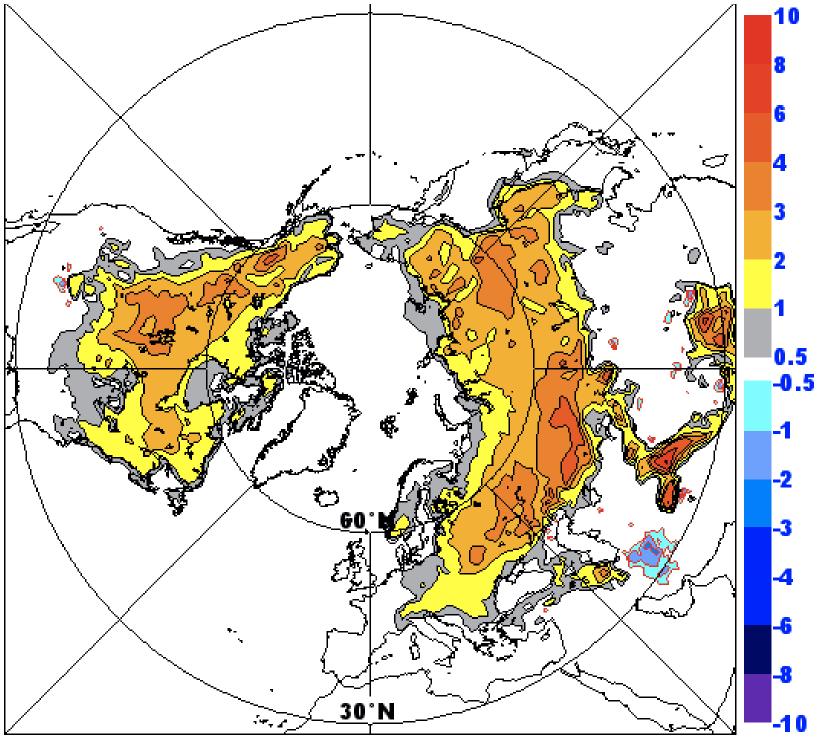
Effect of revised LTG in 2011 model version



ECMWF IFS Courtesy A. Beljaars

Difference in 2m temperature for January 1996

Effect of revised Snow scheme in 2011 model version



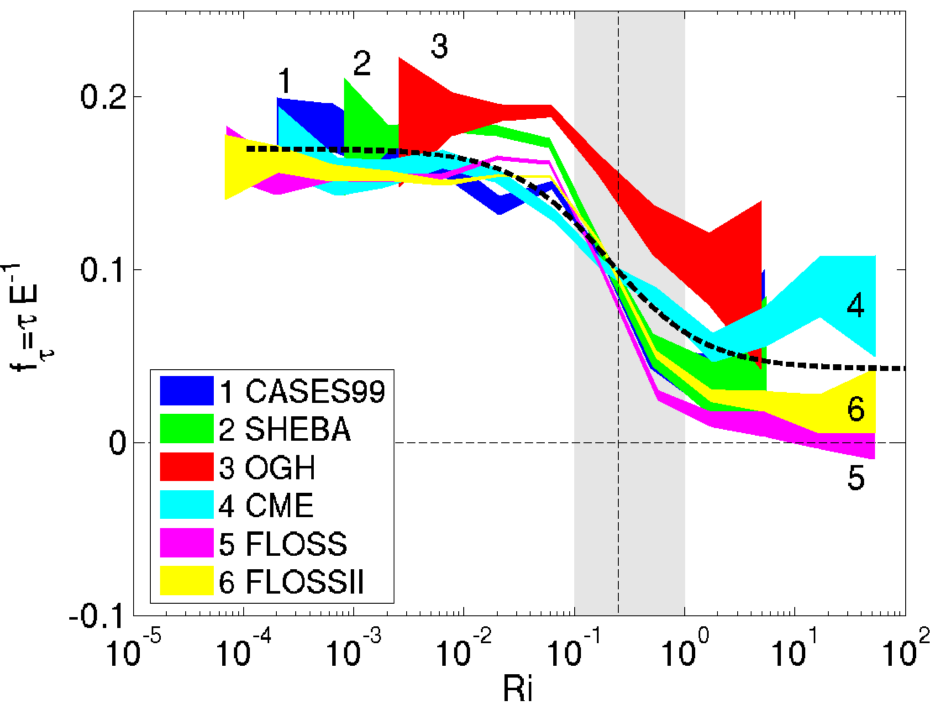
ECMWF IFS Courtesy A. Beljaars

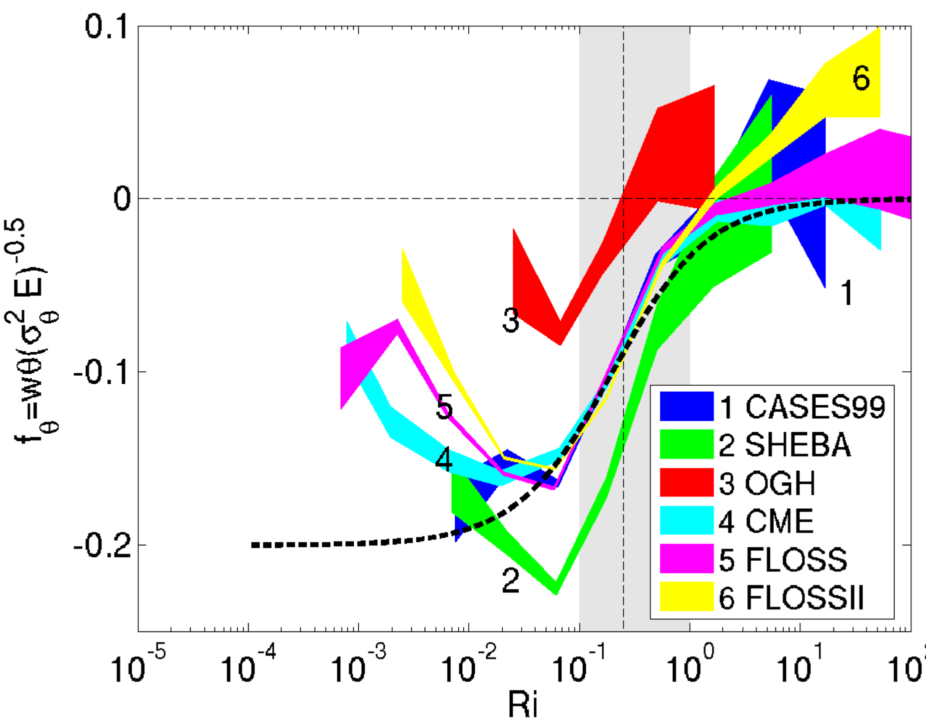
Challenges in modeling the Arctic boundary layer

- Weak turbulence small vertical fluxes (over ice/snow) – stably stratified conditions are challenging
- Non-homogeneous surfaces, strong contrasts and non-stationary conditions
- Shallow layers – vertical resolution is an issue
- Conditions are not ”reset” as often as over mid-latitude land – long-lived stable layers
- Waves and other non-local contributions to turbulence
- Cold temperatures and thereby low humidity content – low water content clouds interact less with radiation
- Convective conditions (flow from ice/snow over ocean and over leads)

Stability functions

5.5 years of turbulence data



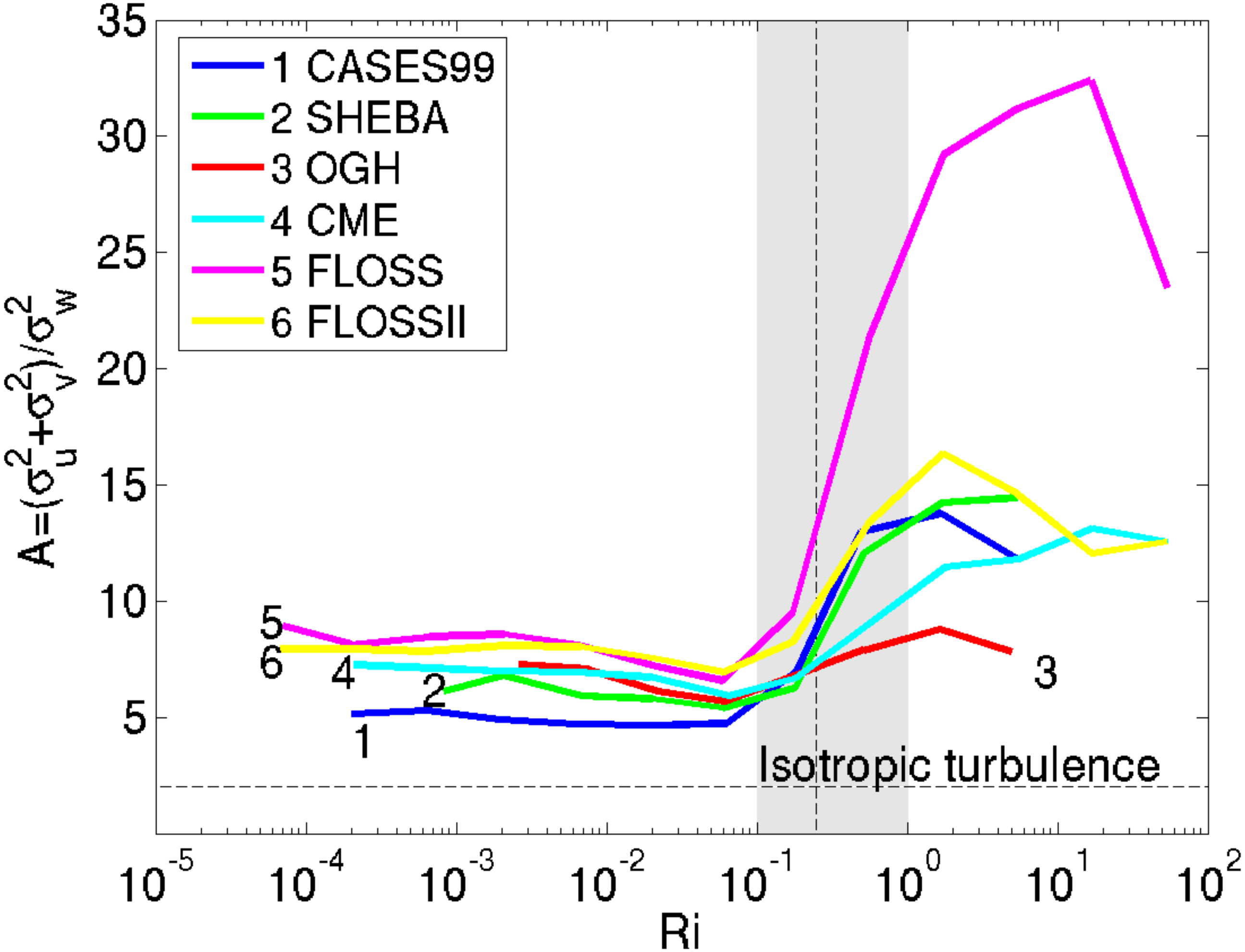


$$\boxed{f_\tau = 0.17(0.25 + 0.75(1 + 4Ri)^{-1})}$$

$$\boxed{f_\theta = -0.145(1 + 4Ri)^{-1}}$$

Mauritsen and Svensson, 2007

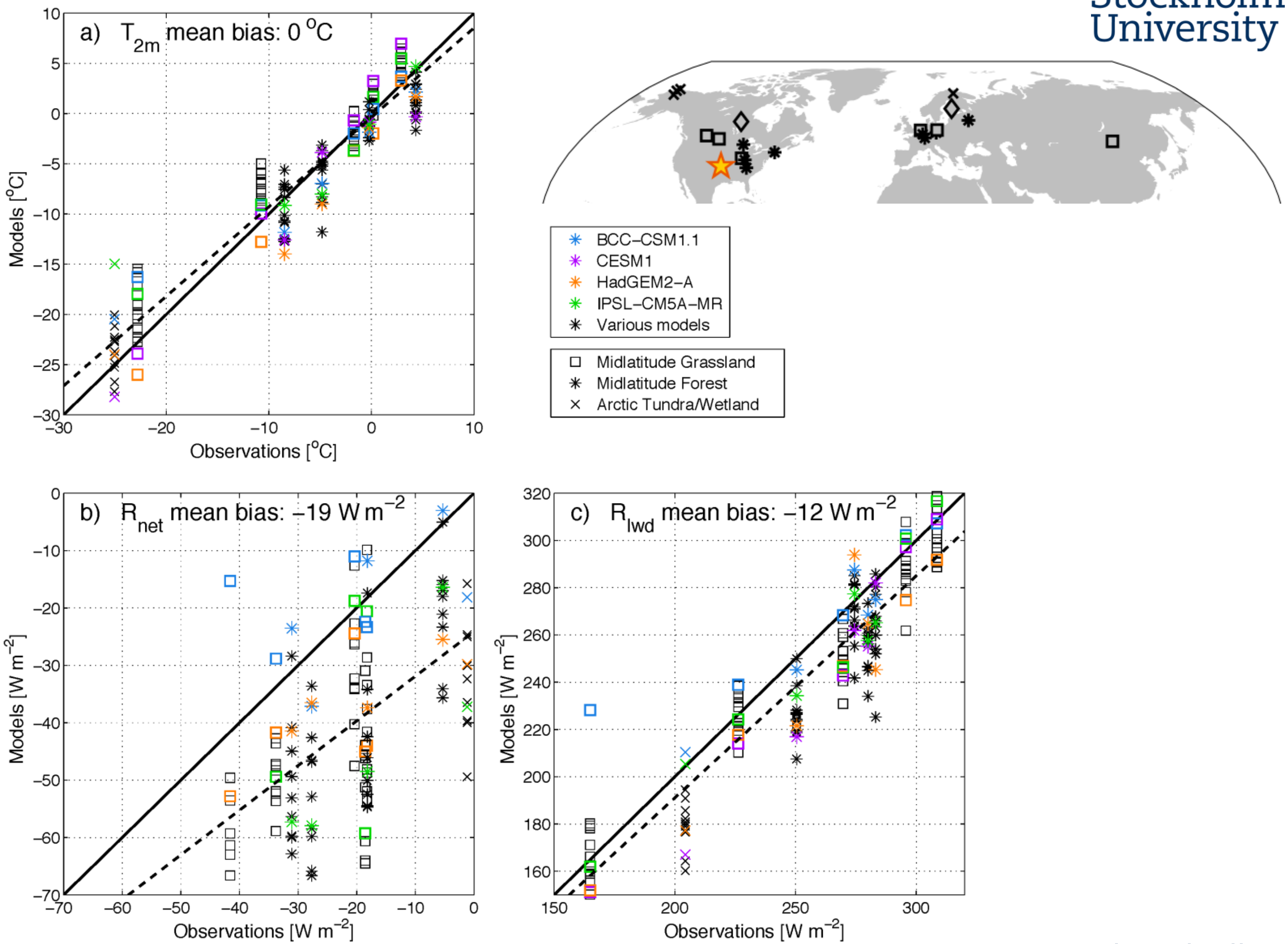
Anisotropy



Mauritsen and Svensson, 2007

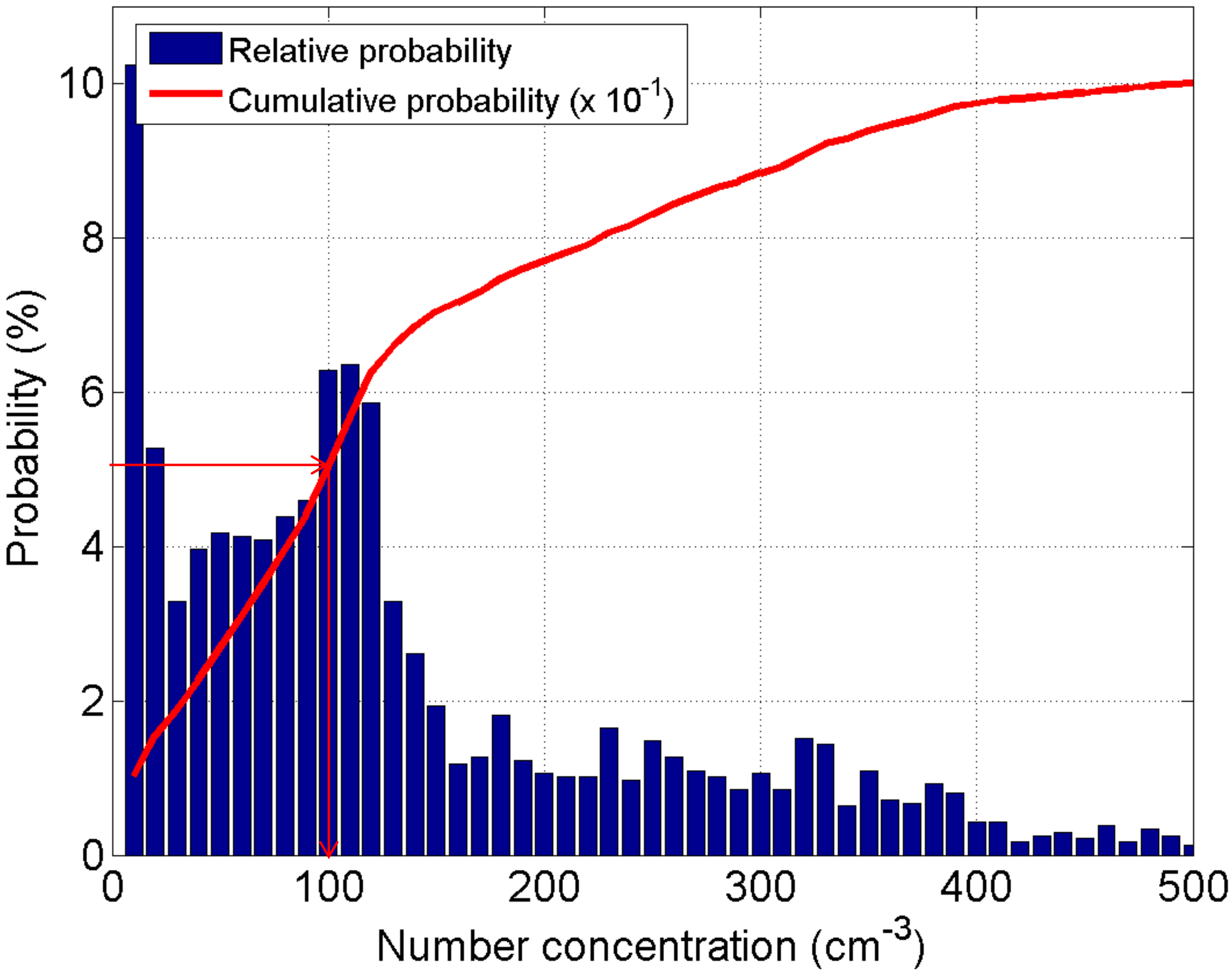
Nighttime temperature and radiation

Flux tower observations and CMIP5 models



Svensson and Lindvall 2015

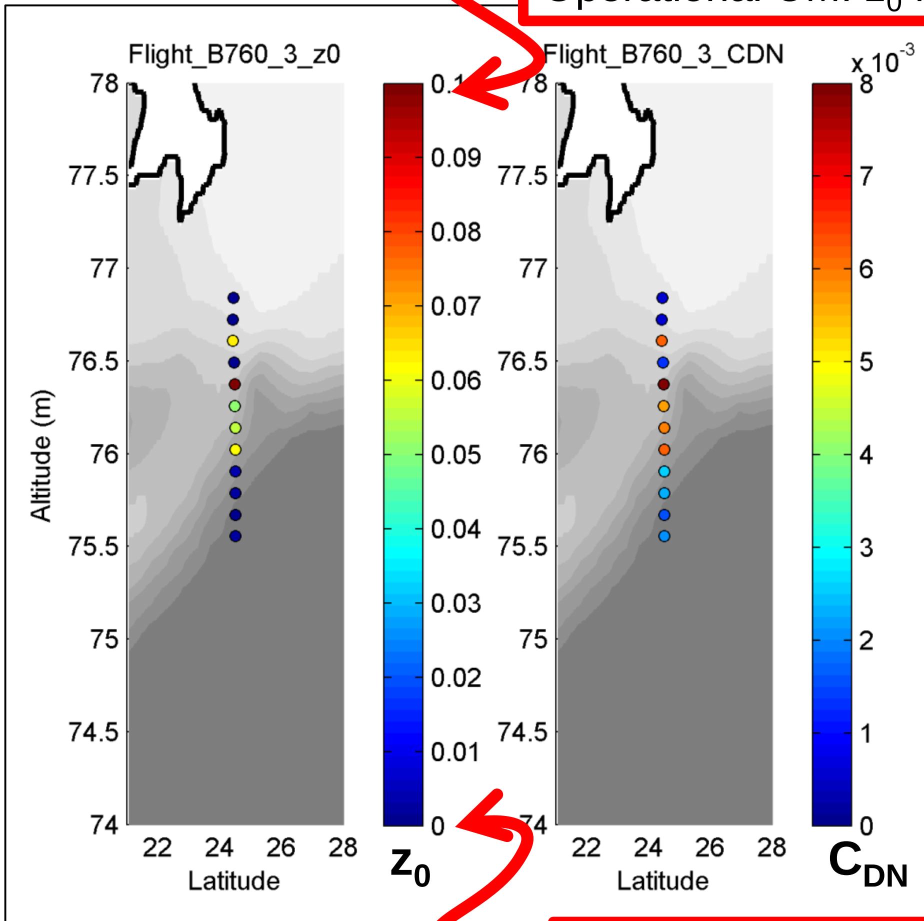
Low concentration of aerosols in summer, even fewer CCN ...

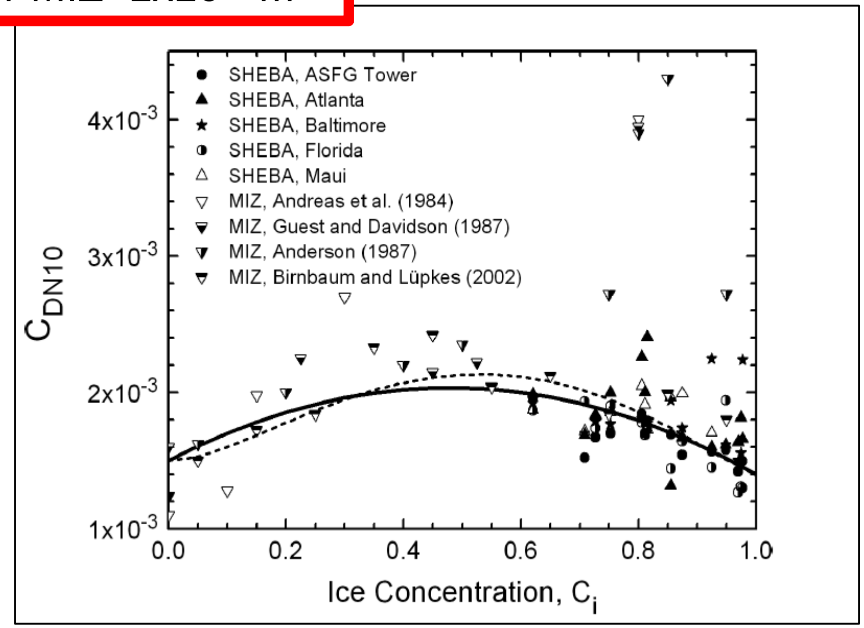


Courtesy Michael Tjernström

Surface Drag Coefficient over sea ice

Operational UM: z_0 for MIZ=1×10^{-1} m



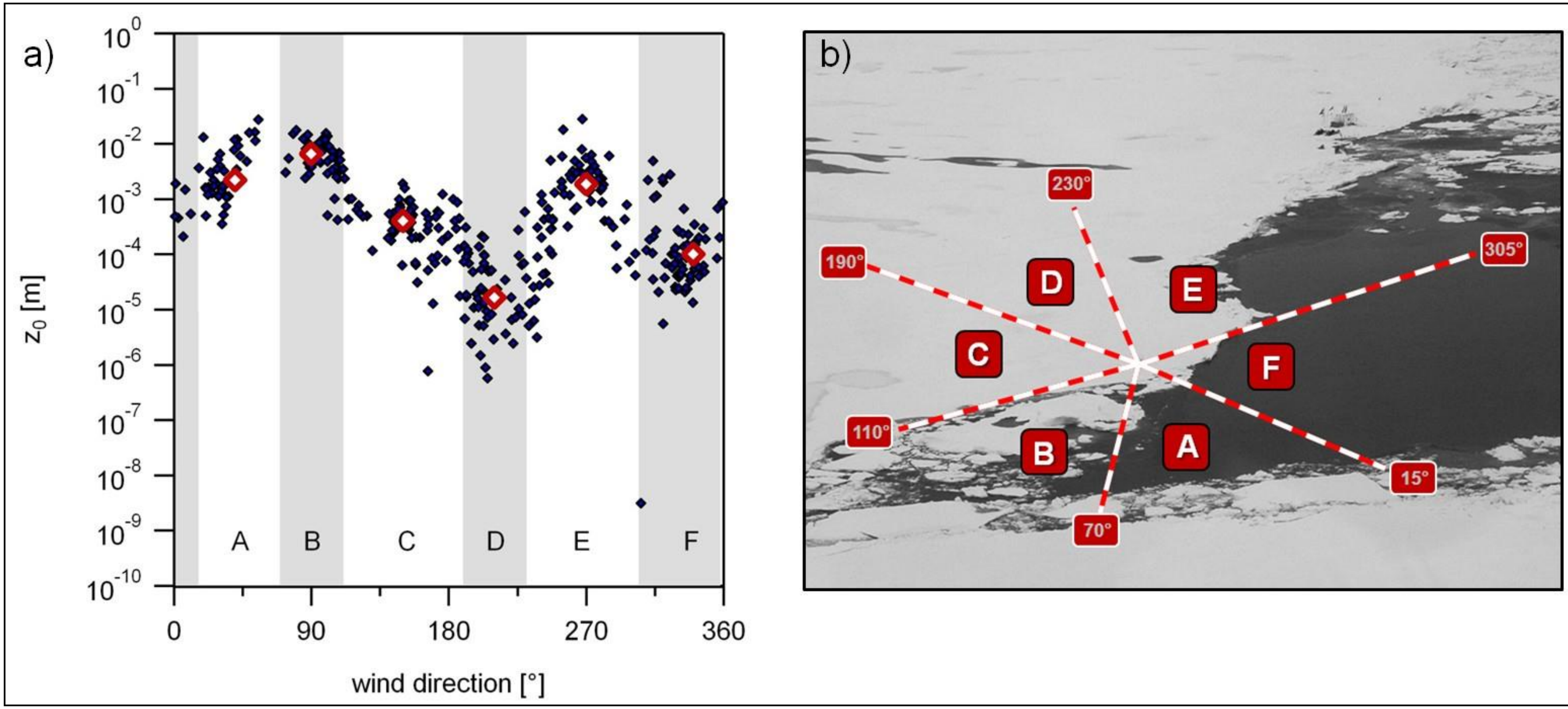


Andreas et al. 2010

HadGEM: z_0 for sea ice and MIZ = 0.5×10^{-4} m

Courtesy of Andy Elvidge, Ian Renfrew and Ian Brooks

Surface type & roughness length



Z_0 varies by at least 3 orders of magnitude over different surface ice conditions

Courtesy of Ian Brooks

Airmass transformation

Transport in over sea ice in winter

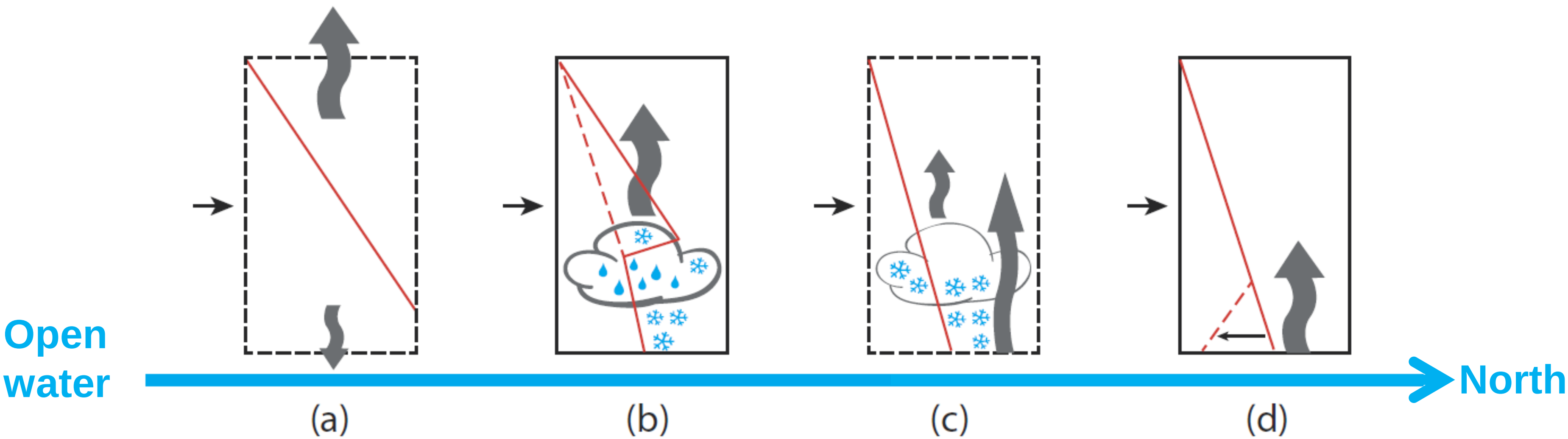


Fig. 6 Sketch of the formation of Arctic air. Dashed boxes mark unstable transition states.

Pithan et al., 2013

Airmass transformation

Transport in over sea ice in winter

Stockholm University

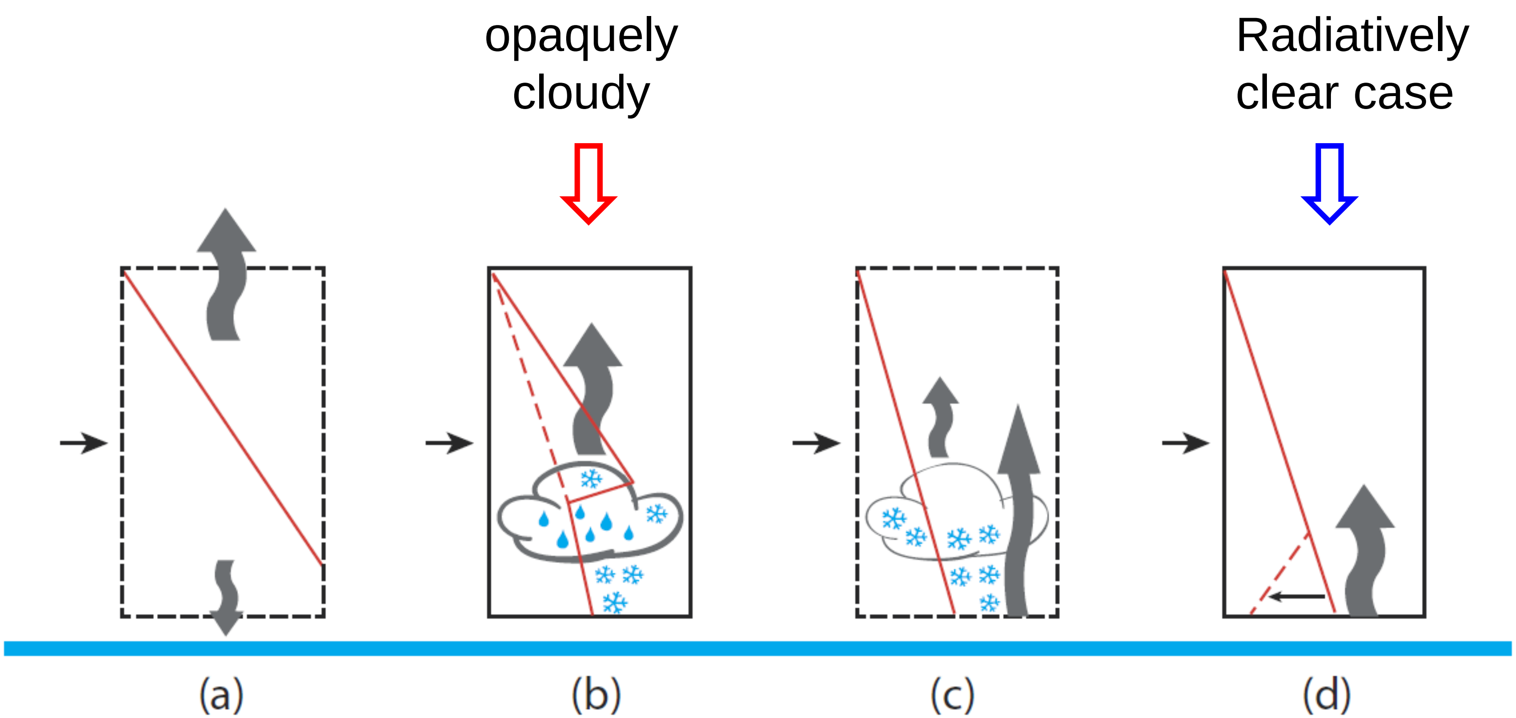
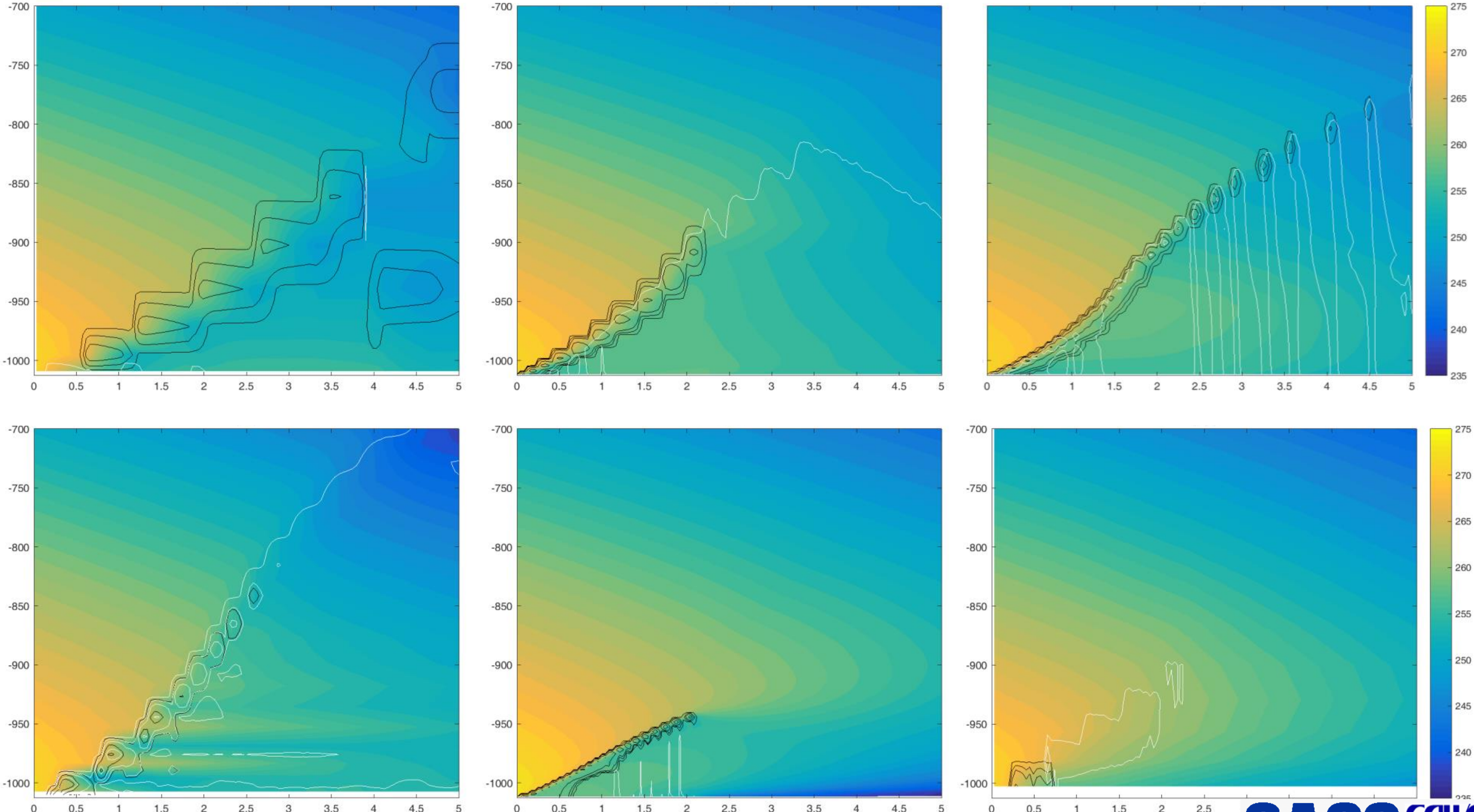


Fig. 6 Sketch of the formation of Arctic air. Dashed boxes mark unstable transition states.

Pithan et al., 2013

Polar airmass transition

GASS SCM model intercomparison – preliminary results



Polar airmass transition

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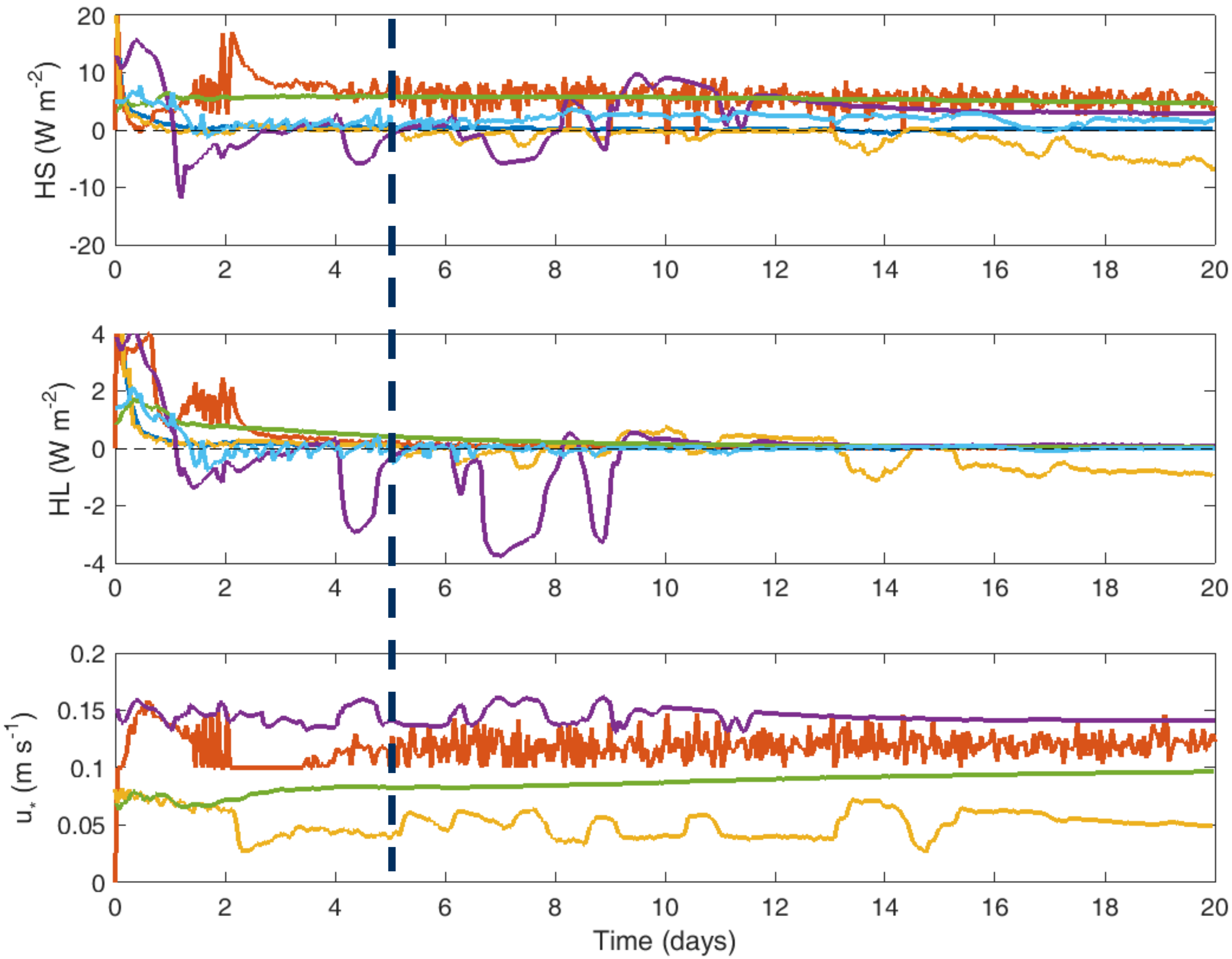

Preliminary results

Polar airmass transition

GASS SCM model intercomparison – preliminary results

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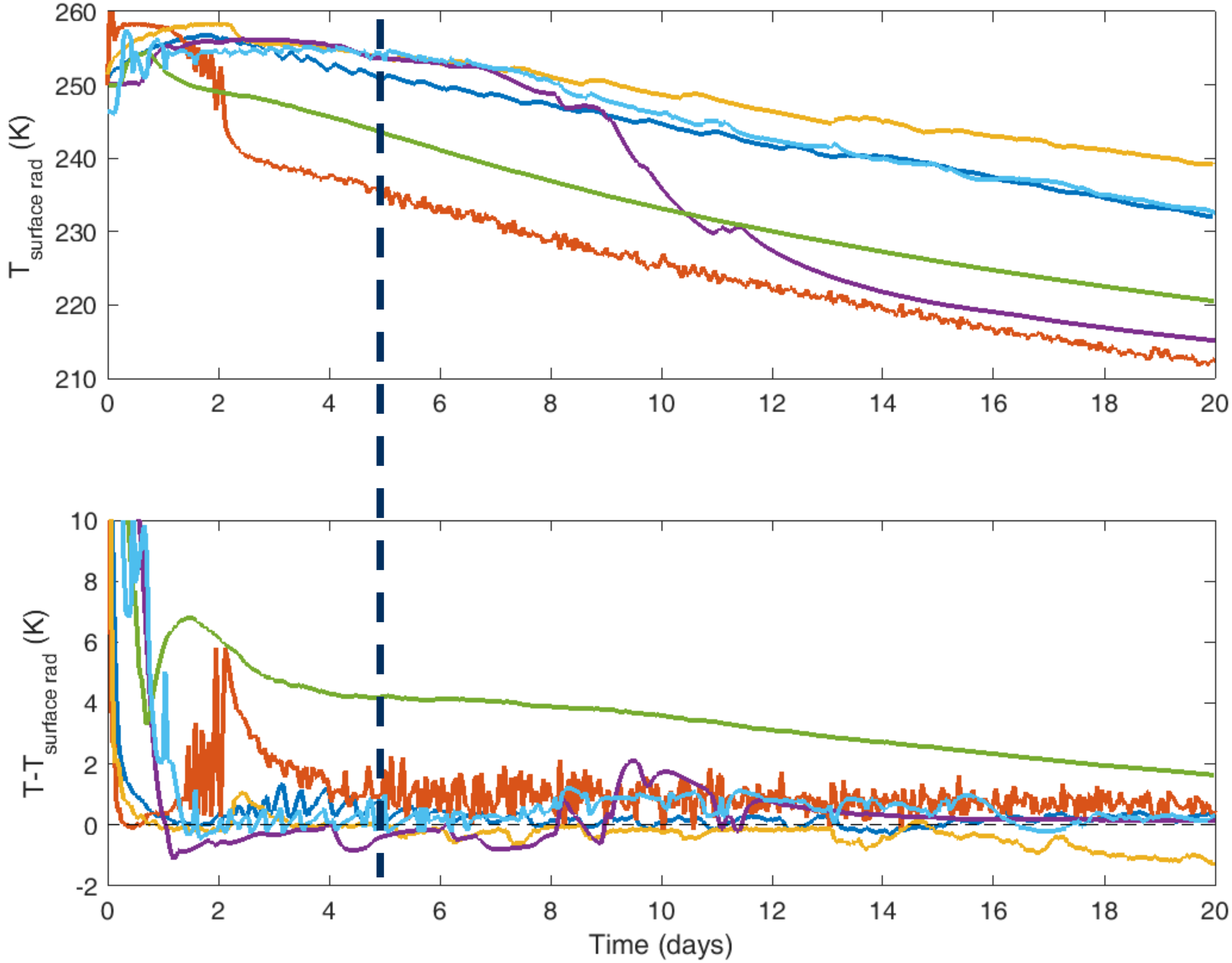
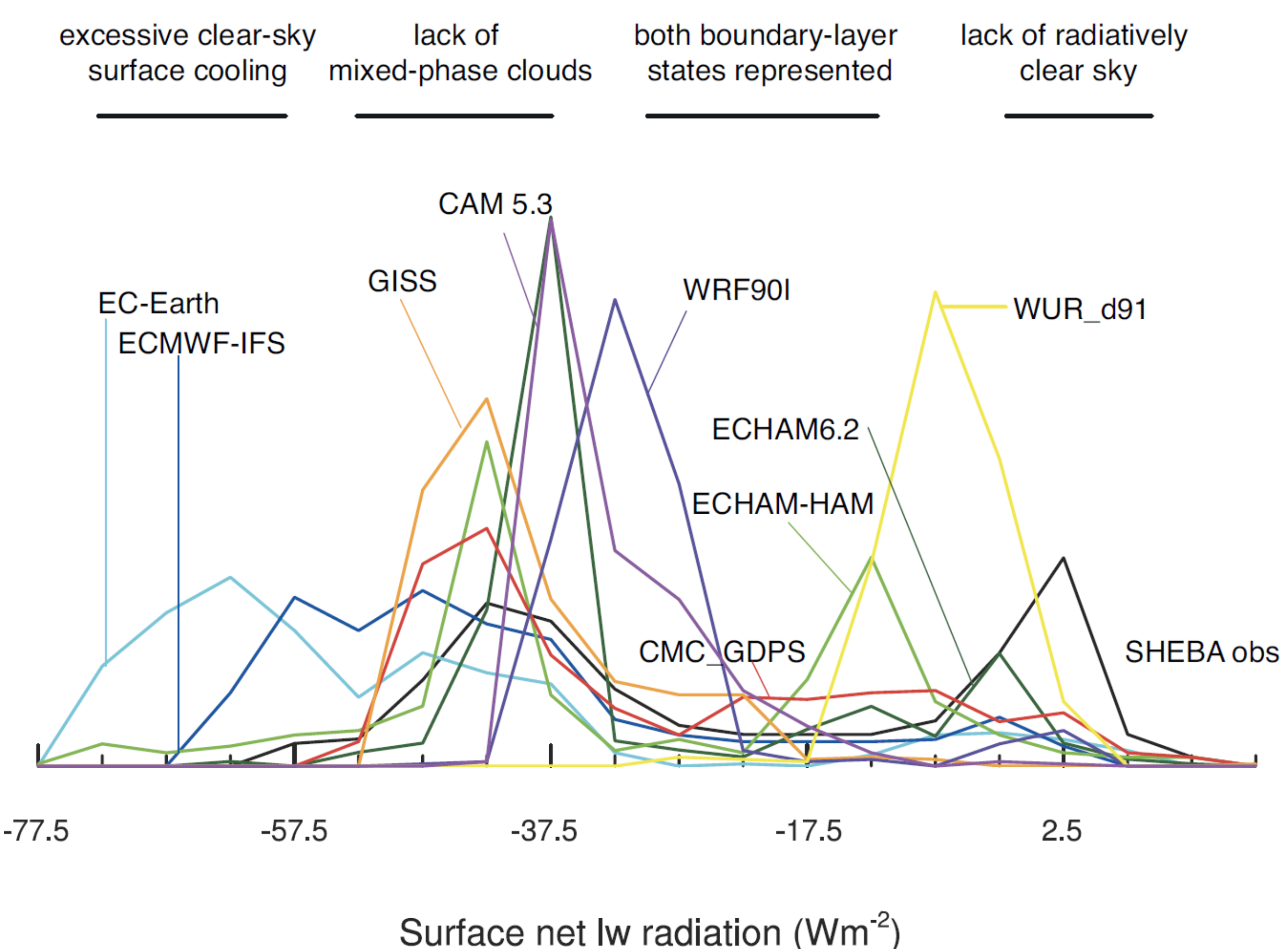


GASS GEWEX WCRP Global Atmospheric System Studies

Preliminary results

Polar airmass transition
GASS SCM model intercomparison

Stockholm University

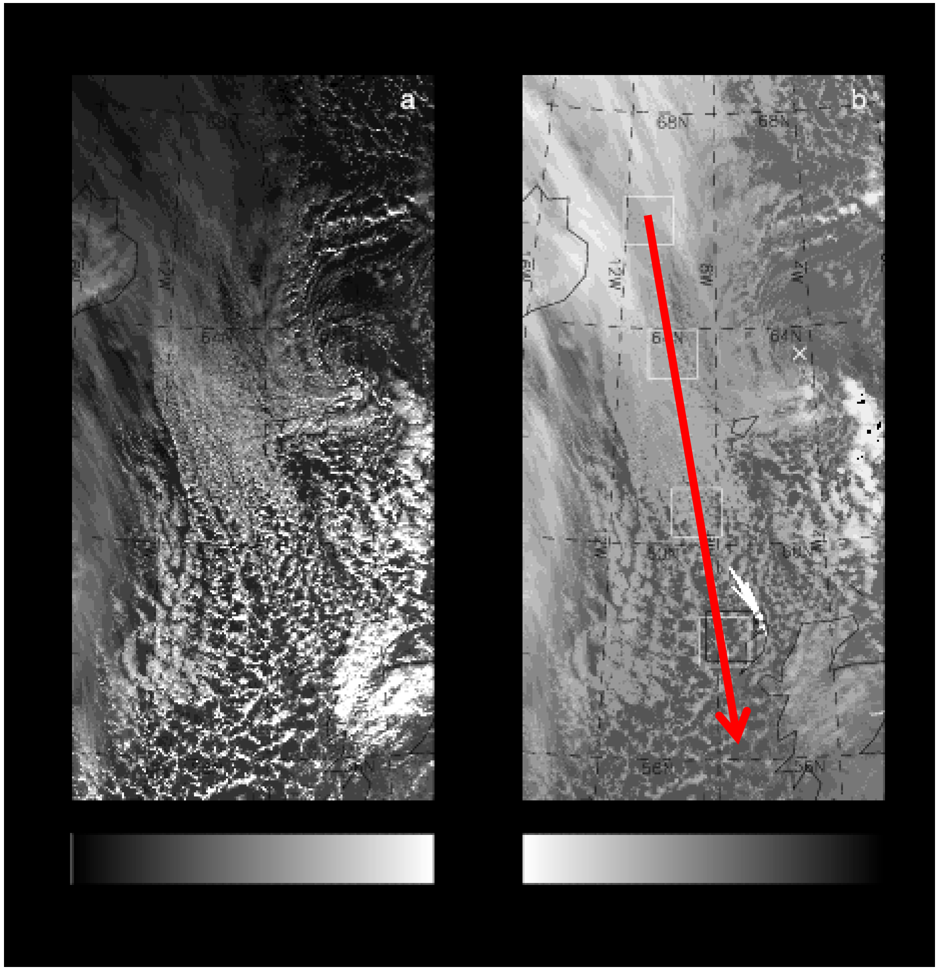


GASS GEWEX WCRP Global Atmospheric System Studies

Air mass transformation – cold air outbreak

Grey Zone Project a WGNE GASS initiative

Stockholm University

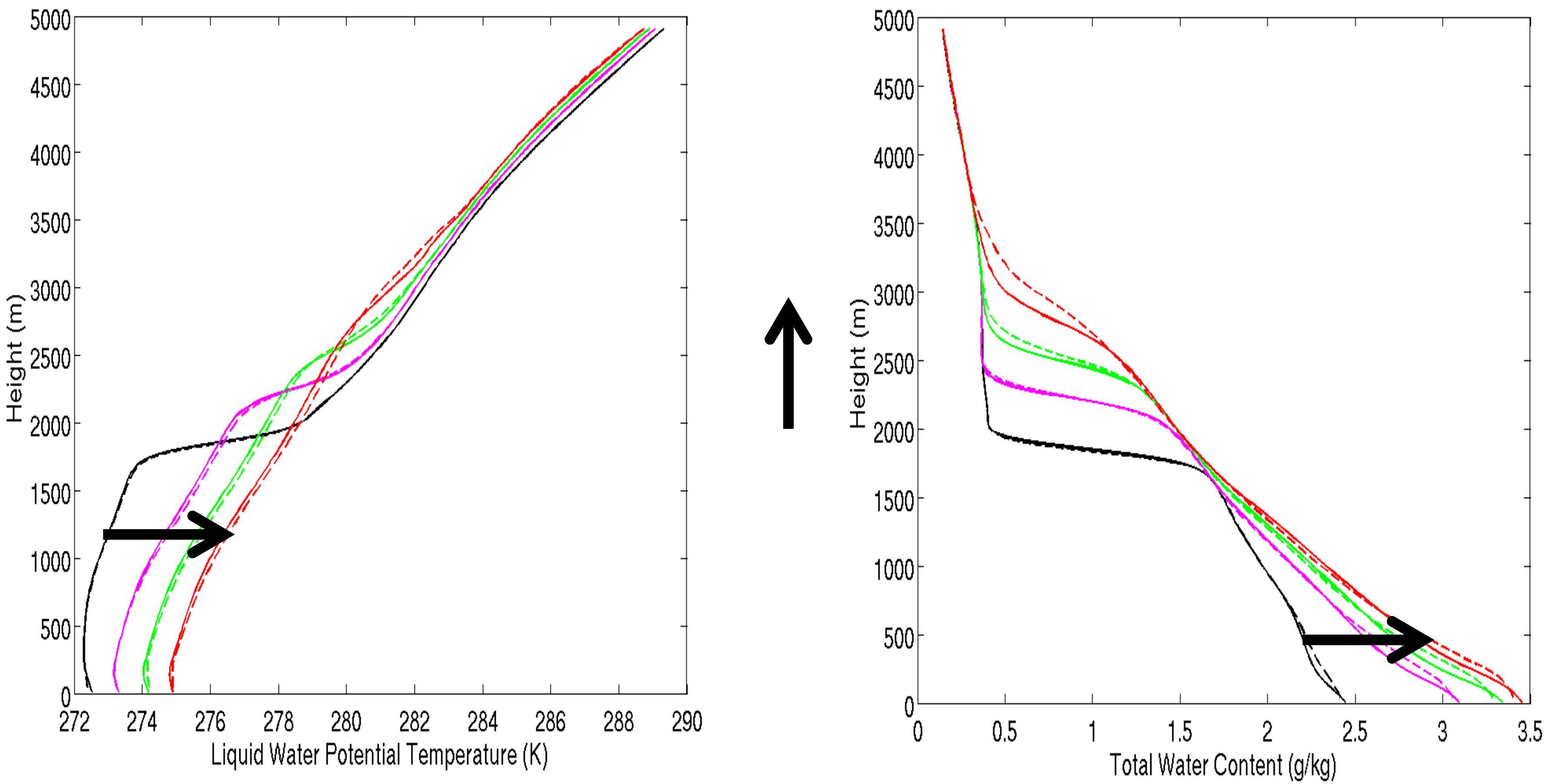


Model intercomparison case for LES, regional and global models

About 14 hours travel time

www.knmi.nl/samenw/greyzone

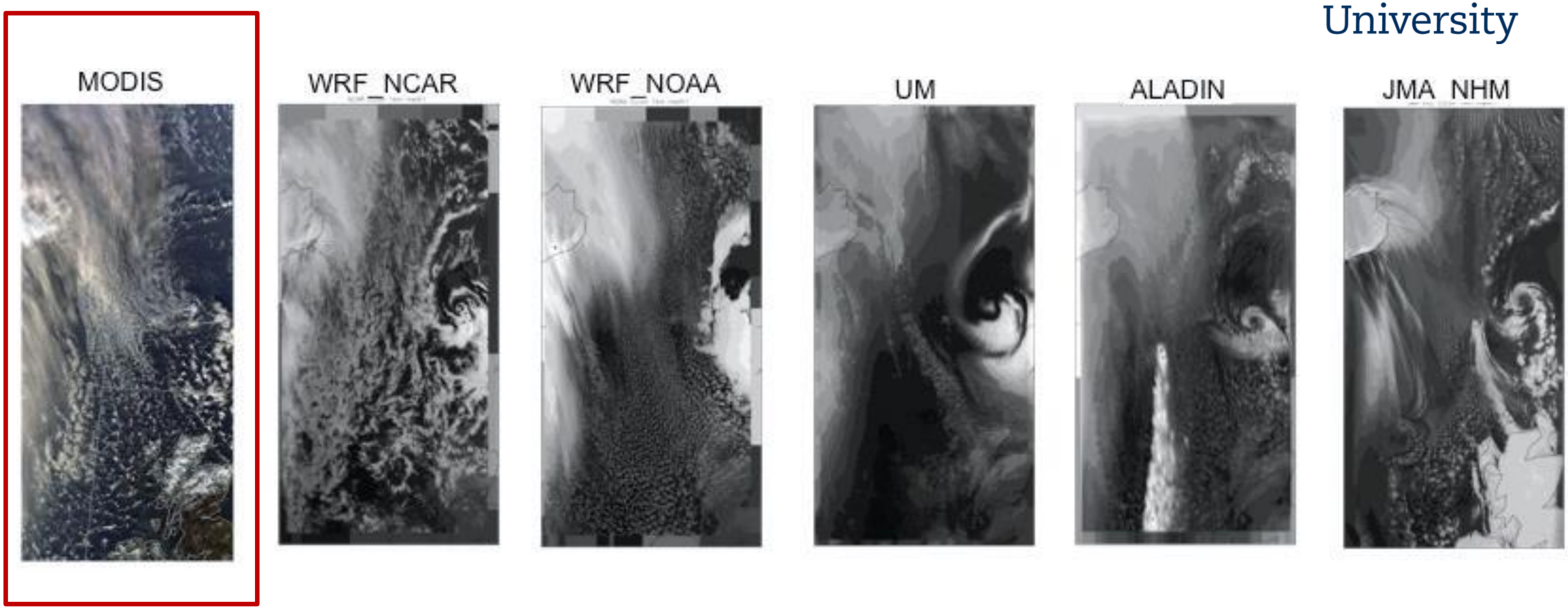
Grey Zone Project
LES results



3 hours
13 hours

www.knmi.nl/samenw/greyzone

Grey Zone Project
Regional model results



” … the uncertainties in microphysics and boundary layer mixing are a larger source of errors than the potential lack of scale-awareness of the convection schemes used.”

Siebesma, 2015