Arctic Boundary Layer

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The Arctic

Photo: Barbara Brooks
Arctic energy budget

Sustained imbalance of 1 Wm$^{-2}$ corresponds to annual melt of 0.1 m sea ice

Arctic sea-ice extent anomaly (October)

NSIDC.org
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
Numerical concerns
Averaged initial tendencies of temperature (IFS)

(a) Arctic: Sea ice-free ocean (DJF)

(b) Arctic: Sea ice-covered ocean (DJF)

(c) NH Mid-latitude oceans (DJF)

(d) Tropical oceans (DJF)

Jung et al. 2015
Synoptic variability

SHEBA

Winter

Near surface temperature (°C)

Days relative to 1 January 1998

Summer

Near surface temperature (°C)

Days relative to 1 January 1998

Spring

Near surface temperature (°C)

Days relative to 1 January 1998

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
At a particular Arctic location (SHEBA point) there are $O(10)$ synoptic events each winter.
Lowest layers
Mean profiles @ SHEBA

Curtesy of Ola Persson
Arctic troposphere vertical structure
SHEBA

Winter

Capping inversion

Sometimes near-neutral,…

…sometimes stable

Summer

Less stable, but deeper free troposphere

Weaker inversion

Fewer stable

Tjernström & Graversen 2009
Surface inversion

Elevated inversion

"Boundary layer"

Thermal structure

<table>
<thead>
<tr>
<th></th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
<th>Autumn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>53%</td>
<td>15%</td>
<td>9%</td>
<td>61%</td>
</tr>
<tr>
<td>Elevated</td>
<td>47%</td>
<td>85%</td>
<td>91%</td>
<td>39%</td>
</tr>
</tbody>
</table>

Tjernström & Graversen 2009
Low-level stability
Winter, >64°N, CMIP5 models and ERA

Ocean

Land

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

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

Ocean

Land

Surface sensible heat flux (Wm$^{-2}$)

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...

- 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 \( q_{\text{H_f}} \) and \( \theta_L \) 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
Coupled and uncoupled PBLs
Dissipation rate observed during ASCOS

The whole layer is connected by mixing

Only the cloud layer is mixing

Courtesy Matt Shupe
Importance of the Arctic boundary layer

- 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

Synoptic scale

Spectral-gap?

Coriolis

Diurnal

3.65 days

Scalar mean wind

Longitudinal

Transverse

Vertical

Macroscale

"Inertial subrange"

Kolmogorovs microscale

Taylors microscale

Courtesy M. Tjernström
In equation form ...

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

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

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

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

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

... where the challenge is to model the turbulent diffusivity coefficients $K_M$ and $K_H$
First order closure

\[ w' c' = -K \frac{\partial C}{\partial z} \]

Turbulent flux

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

Diffusivity K depends on characteristics of turbulent flow

\[ l : \text{length scale} \]

\[ Ri = \frac{g \frac{\partial \theta}{\partial z}}{\frac{\partial U}{\partial z}} \left/ \left| \frac{\partial U}{\partial z} \right|^2 \right. \]

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 length-scale, in combination with prognostic 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
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

Enhanced friction “needed” in models

and heat
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

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

\[ f_\theta = -0.145(1 + 4Ri)^{-1} \]

Mauritsen and Svensson, 2007
Anisotropy

Mauritsen and Svensson, 2007
Nighttime temperature and radiation
Flux tower observations and CMIP5 models

(a) $T_{2m}$ mean bias: 0 °C

(b) $R_{net}$ mean bias: $-19 \text{ W m}^{-2}$

(c) $R_{hwd}$ mean bias: $-12 \text{ W m}^{-2}$

Svensson and Lindvall 2015
Low concentration of aerosols in summer, even fewer CCN ...
Surface Drag Coefficient over sea ice

Operational UM: $z_0$ for MIZ = $1 \times 10^{-1}$ m

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

Andreas et al. 2010

Courtesy of Andy Elvidge, Ian Renfrew and Ian Brooks
Surface type & roughness length

\[ Z_0 \text{ varies by at least 3 orders of magnitude over different surface ice conditions} \]
Airmass transformation
Transport in over sea ice in winter

Fig. 6 Sketch of the formation of Arctic air. Dashed boxes mark unstable transition states.
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
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
Polar airmass transition
GASS SCM model intercomparison

Excessive clear-sky surface cooling
Lack of mixed-phase clouds
Both boundary-layer states represented
Lack of radiatively clear sky

Surface net lw radiation (Wm⁻²)
Air mass transformation – cold air outbreak
Grey Zone Project a WGNE GASS initiative

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.”