

Transport Implications for Arctic Air quality and Meteorology

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The 2017 Connaught Summer Institute in Arctic Science:
Atmosphere, Cryosphere, and Climate

July 16, 2017

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Outline

Introduction

Atmospheric Turbulence

Transport Modelling

Planetary Boundary Layer (PBL)

Definition

Equations

Arctic

Case Study 1

Mixing Height (MH)

MH Models

MH Observations

Case Study 2

Turbulent Flux

Flux Models

Flux Observations

Conclusions

Closing

Introduction

Atmospheric
Turbulence

Transport Modelling

Planetary Boundary Layer (PBL)

Definition

Equations

Arctic

Case Study 1

Mixing Height (MH)

MH Models

MH Observations

Case Study 2

Turbulent Flux

Flux Models

Flux Observations

Conclusions

Closing

Introduction

Atmospheric Turbulence

A zonal-mean flow field is said to be hydro-dynamically unstable if a small disturbance introduced into the flow grows spontaneously, drawing energy from the mean flow

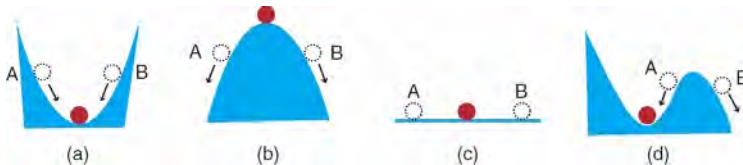


Figure: Perturbation and Stability Concept: (a) Unconditionally Stable (b) Unconditionally Unstable (c) Neutral (d) Conditionally Stable (www.geog.ucsb.edu).

Introduction

Atmospheric Turbulence

Transport Modelling

Planetary

Boundary Layer (PBL)

Definition

Equations

Arctic

Case Study 1

Mixing Height (MH)

MH Models

MH Observations

Case Study 2

Turbulent Flux

Flux Models

Flux Observations

Conclusions

Closing

Introduction

Atmospheric Turbulence

- ▶ In fluid dynamics, **turbulence** or turbulent flow is a flow regime characterized by **chaotic** property changes.
- ▶ Turbulence is **difficult** to **understand**, **measure**, and **model**.
- ▶ Turbulence in the **atmosphere** and **hydrosphere** is the **dominating force** in **atmospheric transport**.

Introduction

Atmospheric Turbulence

Transport Modelling

Planetary

Boundary Layer (PBL)

Definition

Equations

Arctic

Case Study 1

Mixing Height (MH)

MH Models

MH Observations

Case Study 2

Turbulent Flux

Flux Models

Flux Observations

Conclusions

Closing

Introduction

Atmospheric Turbulence

- ▶ Turbulence can be perceived as the presence of **eddies** in the fluid.
- ▶ **eddy**: is a local structure of a fluid that **spins**.
- ▶ **Turbulent energy cascade**: turbulence begins with formation of large eddies due to **instability** that subsequently break down to form smaller and smaller eddies due to subsequent instabilities until they are so small that they are damped by **viscous dissipation**.

In a famous poem by **Lewis Richardson** (1881-1953):

“Big whirls have little whirls that feed on their velocity, and little whirls have lesser whirls and so on to viscosity”.

Introduction

Atmospheric Turbulence

Transport Modelling

Planetary

Boundary Layer (PBL)

Definition

Equations

Arctic

Case Study 1

Mixing Height (MH)

MH Models

MH Observations

Case Study 2

Turbulent Flux

Flux Models

Flux Observations

Conclusions

Closing

Introduction

Atmospheric Turbulence

Graphical presentation of the turbulent energy cascade: e.g. dissipation of a cigarette smoke ring!

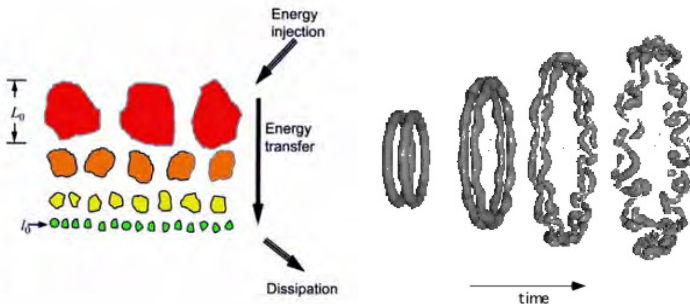


Figure: Representation of turbulent energy cascade (<http://career.ammarica.net>, <http://pages.jh.edu>).

Introduction

Transport Modelling



Figure: From left to right and top to bottom: J. V. **Boussinesq** (1842-1929, France); O. **Reynolds** (1842-1912, U.K.); L. F. **Richardson** (1881-1953, U.K.); G. I. **Taylor** (1886-1975, U.K.); L. **Prandtl** (1875-1953, Germany); A. N. **Kolmogorov** (1903-1987, U.S.S.R.); T. **von Karman** (1881-1963, Hungary-U.S.A.); J. **Deardorff** (1928-, U.S.A.)

Transport
Implications for
Arctic Air quality
and Meteorology

Amir A. Aliabadi

Introduction

Atmospheric
Turbulence

Transport Modelling

Planetary

Boundary Layer
(PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

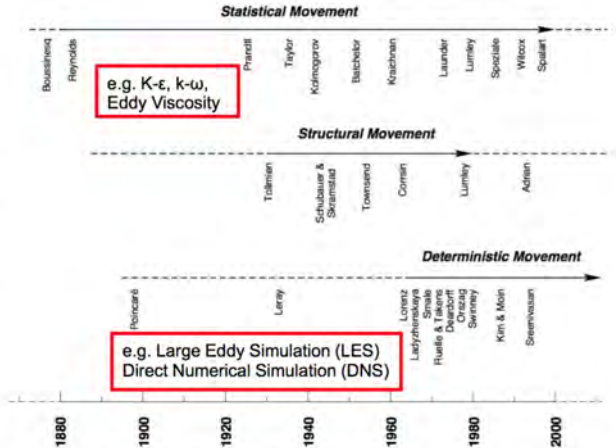
Introduction

Transport Modelling

Transport
Implications for
Arctic Air quality
and Meteorology

Amir A. Aliabadi

Historical Developments in Turbulent Flows



Chapman & Tobak, 1985, Observations, Theoretical Ideas, and Modelling of Turbulent Flows – Past, Present, and Future (Photo Credit)

Introduction

Atmospheric
Turbulence

Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Introduction

Transport Modelling

- ▶ Predicting fluid flow requires solution of the **Navier-Stokes** or **Lattice-Boltzmann** equations.
- ▶ The **exact simulation** of these equations for **turbulent flow** is **impossible** for many practical engineering applications because the **computational cost** of doing so is **extremely prohibitive**.
- ▶ As a result, turbulence is usually **modelled** by construction and use of **approximations and hypotheses** to predict the effects of turbulence.
- ▶ Common models for turbulence are: **1) Aerodynamic Resistance, 2) Lower Dimension, 3) Reynolds-Averaged Navier-Stokes, 4) Large Eddy Simulation, and 5) Direct Numerical Simulation** models.

Introduction

Atmospheric
Turbulence

Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

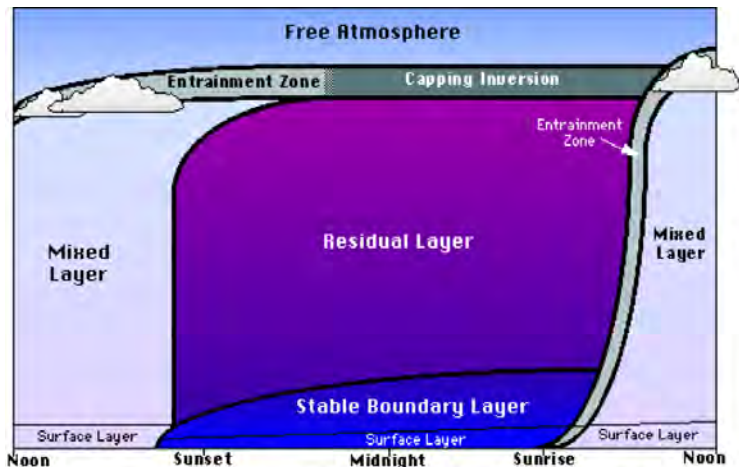
Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Planetary Boundary Layer (PBL)

Definition



Structure of Planetary Boundary Layer

adapted from Stull, 1988.

Transport
Implications for
Arctic Air quality
and Meteorology

Amir A. Aliabadi

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary
Boundary Layer
(PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Planetary Boundary Layer (PBL)

Equations

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

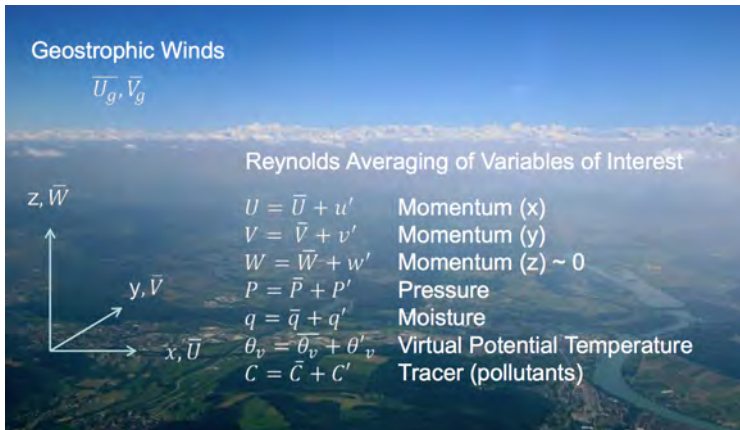
Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing



Geostrophic Winds

$$\overline{U}_g, \overline{V}_g$$

Reynolds Averaging of Variables of Interest

$U = \overline{U} + u'$	Momentum (x)
$V = \overline{V} + v'$	Momentum (y)
$W = \overline{W} + w'$	Momentum (z) ~ 0
$P = \overline{P} + P'$	Pressure
$q = \overline{q} + q'$	Moisture
$\theta_v = \overline{\theta}_v + \theta'_v$	Virtual Potential Temperature
$C = \overline{C} + C'$	Tracer (pollutants)

Diagram showing a 3D coordinate system with axes labeled x, \overline{U} , y, \overline{V} , and z, \overline{W} .

Planetary Boundary Layer (PBL)

Equations

Ideal Gas

$$\frac{P}{R} = \rho \bar{T}_v$$

Continuity

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

x-Momentum

$$\frac{\partial \bar{U}}{\partial t} + \bar{U} \frac{\partial \bar{U}}{\partial x} + \bar{V} \frac{\partial \bar{U}}{\partial y} = f(\bar{V} - \bar{V}_g)$$

y-Momentum

$$\frac{\partial \bar{V}}{\partial t} + \bar{U} \frac{\partial \bar{V}}{\partial x} + \bar{V} \frac{\partial \bar{V}}{\partial y} = f(\bar{U}_g - \bar{U})$$

Moisture

$$\frac{\partial \bar{q}}{\partial t} + \bar{U} \frac{\partial \bar{q}}{\partial x} + \bar{V} \frac{\partial \bar{q}}{\partial y} = \frac{S_q}{\bar{\rho}}$$

Virt. Pot. Temp.

$$\frac{\partial \bar{\theta}}{\partial t} + \bar{U} \frac{\partial \bar{\theta}}{\partial x} + \bar{V} \frac{\partial \bar{\theta}}{\partial y} = -\frac{1}{\bar{\rho} C_p} \left[L_v E + \frac{\partial \bar{Q}_j^*}{\partial x_j} \right]$$

Tracer

$$\frac{\partial \bar{C}}{\partial t} + \bar{U} \frac{\partial \bar{C}}{\partial x} + \bar{V} \frac{\partial \bar{C}}{\partial y} = \frac{S_C}{\bar{\rho}}$$

**Turbulent Fluxes
Need to be Modelled**

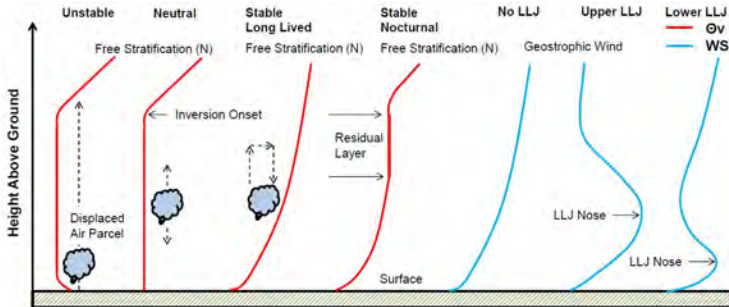
$$\begin{aligned} & -\frac{\partial \overline{u'w'}}{\partial z} \\ & -\frac{\partial \overline{v'w'}}{\partial z} \\ & -\frac{\partial \overline{q'w'}}{\partial z} \\ & -\frac{\partial \overline{\theta_v'w'}}{\partial z} \\ & -\frac{\partial \overline{C'w'}}{\partial z} \end{aligned}$$

Stull, 1988, Introduction to Boundary Layer Meteorology

Case Study 1

Mixing Height (MH)

- ▶ Is a **bulk** and **diagnostic** quantity in the boundary layer.
- ▶ Quantifies the extent of **vertical mixing**.
- ▶ Affects **transport** in **air quality** and **meteorological** studies.
- ▶ Depends on **stability**.



Case Study 1

MH Models

▶ Profile Method Parameters:

- ▶ Bulk Richardson Number: $Ri_B = \frac{hg(\overline{\theta}_v - \overline{\theta}_{v0})}{\overline{\theta}_{v0}(\overline{U}^2 + \overline{V}^2)}$
- ▶ Profiles of Virtual Potential Temperature: $\overline{\theta}_v$
- ▶ Profiles of Wind Speed: \overline{U} , \overline{V}

▶ Surface Method Parameters:

- ▶ Friction Velocity: $u_* = (\overline{u'w'^2} + \overline{v'w'^2})^{1/4}$
- ▶ Obukhov Length: $L = \frac{-\overline{\theta}_v u_*^3}{\kappa g \theta'_v w'}$
- ▶ Brunt-Väisälä Frequency: $N = \left(\frac{g}{\overline{\theta}_v} \frac{\partial \overline{\theta}_v}{\partial z} \right)^{1/2}$

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Case Study 1

MH Observations

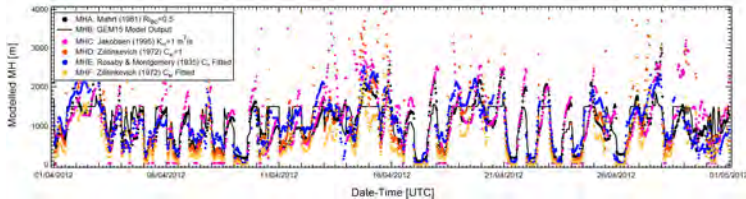


Figure: Lamont: agreement in **profile** and **surface** methods

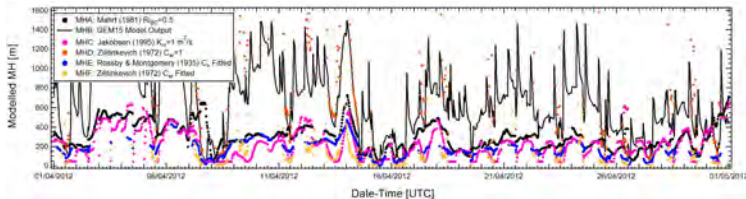


Figure: Barrow: disagreement in **profile** and **surface** methods

Transport
Implications for
Arctic Air quality
and Meteorology

Amir A. Aliabadi

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary
Boundary Layer
(PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Case Study 1

MH Observations

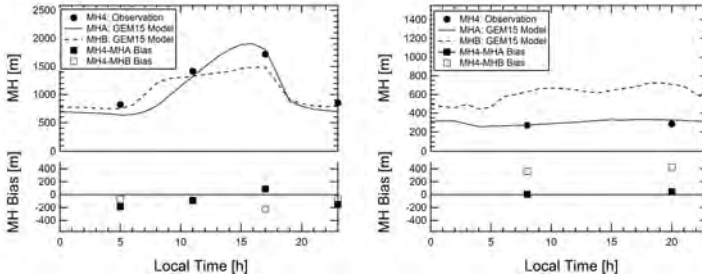


Figure: Comparison of **profile** and **surface** methods for prediction of MH in Lamont (Left) and Barrow (Right) in March-April-May

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Case Study 1

MH Observations

- ▶ **Fit constants** for surface methods **not unique**.
- ▶ Both **surface** and **profile** methods suitable for MH parameterizations in mid latitudes (Lamont).
- ▶ Profile methods suitable for MH parameterization in high latitude with stable boundary layers (Barrow).
- ▶ **Profile** methods **reduce model bias** in MH by a factor of 2 (Barrow).
- ▶ **Profile** methods **improve the statistics** for model versus observation comparison.

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Case Study 2

Flux Models

- ▶ Down-gradient Transport:

$$\overline{u'w'} = -K_m \frac{\partial \bar{U}}{\partial z} \quad (1)$$

$$\overline{\theta'_v w'} = -K_h \frac{\partial \bar{\theta}_v}{\partial z} \quad (2)$$

- ▶ Down- and Counter-gradient Transport:

$$\overline{u'w'} = -K_m \left(\frac{\partial \bar{U}}{\partial z} - \Gamma_m \right) \quad (3)$$

$$\overline{\theta'_v w'} = -K_h \left(\frac{\partial \bar{\theta}_v}{\partial z} - \Gamma_h \right) \quad (4)$$

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Case Study 2

Flux Observations

Transport
Implications for
Arctic Air quality
and Meteorology

Amir A. Aliabadi

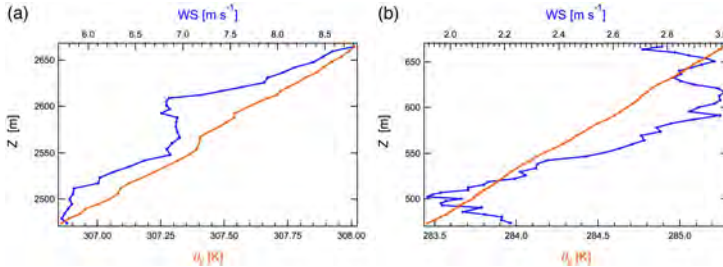


Figure: Profiles of wind speed and virtual potential temperature for down-gradient (left) and counter-gradient (right) cases of flux transport.

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Case Study 2

Flux Observations

Transport
Implications for
Arctic Air quality
and Meteorology

Amir A. Aliabadi

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

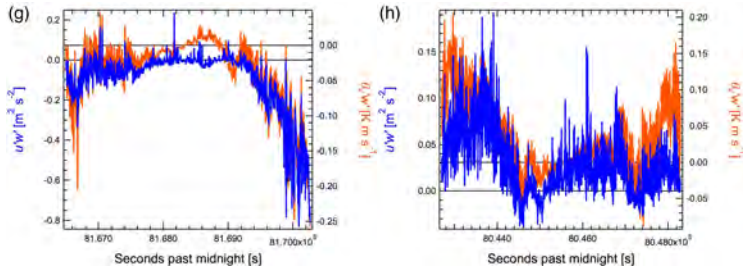


Figure: Time series for momentum and heat flux for **down-gradient** (left) and **counter-gradient** (right) cases of flux transport.

Case Study 2

Flux Observations

Transport
Implications for
Arctic Air quality
and Meteorology

Amir A. Aliabadi

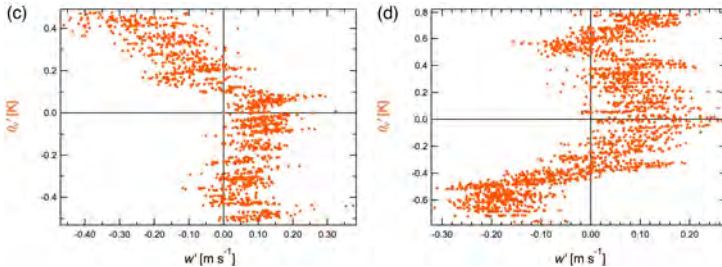


Figure: Quadrant plots for velocity and temperature fluctuations for **down-gradient** (left) and **counter-gradient** (right) cases of **heat flux** transport.

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Case Study 2

Flux Observations

Transport
Implications for
Arctic Air quality
and Meteorology

Amir A. Aliabadi

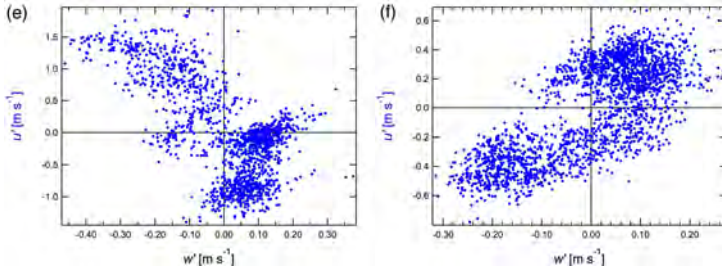


Figure: Quadrant plots for velocity fluctuations for **down-gradient** (left) and **counter-gradient** (right) cases of **momentum flux** transport.

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Case Study 2

Flux Observations

Transport
Implications for
Arctic Air quality
and Meteorology

Amir A. Aliabadi

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

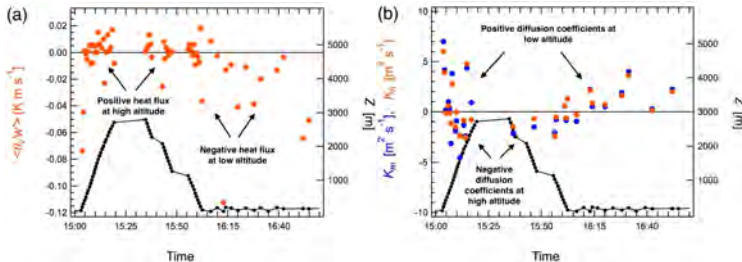


Figure: Heat flux (left) and apparent diffusion coefficients (right) as a function of aircraft altitude.

Case Study 2

Flux Observations

Transport
Implications for
Arctic Air quality
and Meteorology

Amir A. Aliabadi

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

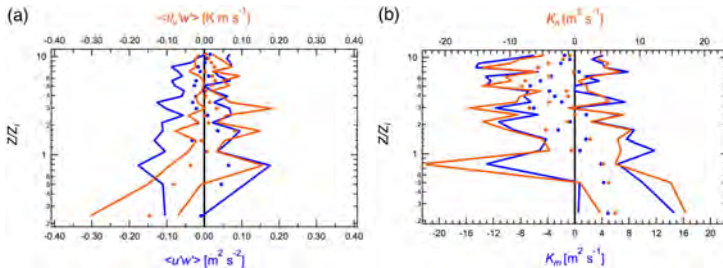


Figure: Heat profiles (left) and apparent diffusion coefficients (right) as a function of height.

Case Study 2

Flux Observations

- ▶ Observation: Heat Flux Profiles
- ▶ Param. 1: Down-, Counter-gradient flux (anisotropic)
- ▶ Param. 2: Down-, Counter-gradient flux (isotropic)
- ▶ Param. 3: Down-gradient flux (isotropic)

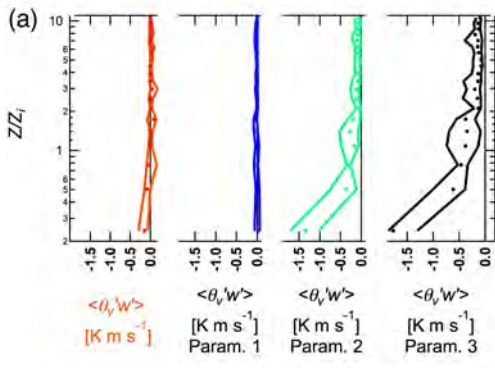


Figure: Heat flux profiles observation and parameterizations.

Case Study 2

Flux Observations

Transport
Implications for
Arctic Air quality
and Meteorology

Amir A. Aliabadi

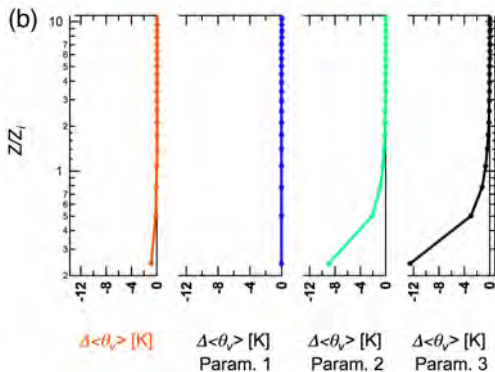


Figure: Temperature change in one model timestep $\Delta t = 500$ s due to heat flux parameterizations.

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Case Study 2

Flux Observations

- ▶ Both **down- and counter-gradient transport** of heat and momentum fluxes occur in the **Arctic lower troposphere**.
- ▶ The classical theory of **down-gradient transport** of turbulent fluxes fails to account for counter-gradient transport.
- ▶ Higher order models accounting for **counter-gradient transport** and **anisotropic turbulence** may improve modelling such turbulent fluxes.

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Conclusions

- ▶ **Turbulence** plays the dominant role in **atmospheric transport**.
- ▶ **Air quality** and **meteorological predictions** require adept prediction of atmospheric transport.
- ▶ **Atmospheric transport** is **unique** and typically characterized by **statically stable conditions** in the **Arctic** and differs substantially from **lower latitudes**.
- ▶ **Turbulence** and **atmospheric transport** must be **modelled** and **parameterized** adequately for **Arctic** predictions.

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Closing

Proverbial Ending

“I am an old man now, and when I die and go to heaven there are two matters on which I hope for enlightenment. One is **quantum electro-dynamics** and the other is the **turbulent motion of fluids**. About the former I am rather optimistic.” Horace Lamb (1932)

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Closing

Further Reading

- ▶ Aliabadi, A. A., Staebler, R. M., de Grandpre, J., Zadra, A., & Vaillancourt, P. A. (2016), 'Comparison of Estimated Atmospheric Boundary Layer Mixing Height in the Arctic and Southern Great Plains under Statically Stable Conditions: Experimental and Numerical Aspects', **Atmosphere-Ocean**, 54(1), 60-74, doi: 10.1080/07055900.2015.1119100.
- ▶ Aliabadi, A. A., Staebler, R. M., Liu, M., & Herber, A. (2016), 'Characterization and Parametrization of Reynolds Stress and Turbulent Heat Flux in the Stably-Stratified Lower Arctic Troposphere Using Aircraft Measurements', **Boundary-Layer Meteorology**, 161(1), 99-126, doi: 10.1007/s10546-016-0164-7.

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Closing

Acknowledgements

- ▶ Environment and Climate Change Canada: Ralf Staebler, Paul Makar, Mike Moran, Wanmin Gong, Stephen Beagley, David Tarasick, Michael Liu, Jean de Grandpré, Ayrton Zadra, Paul Vaillancourt
- ▶ University of Toronto: Jon Abbatt, Julia Burkart
- ▶ Alfred Wegener Institute: Andreas Herber, Hannes Schultz, Christian Konrad, Martin Gehrman
- ▶ Atmospheric Radiation Measurements: Hans Verlinde, Michael Liu, Karen Gibson

Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing

Closing

Theory and Applications of Turbulence

Theory and Applications of Turbulence

- ▶ Offering Term: Winter 2018
- ▶ Instructor: Amir A. Aliabadi
- ▶ Applications: Mechanical Engineering, Water Resources Engineering, Environmental Engineering, Biomedical Engineering, Biological Engineering, Computer Engineering, Engineering Systems and Computing, Physics, Chemistry, Geography, Environmental Science
- ▶ Course Activities: History, Theory, Applications, Turbulence Model Design, Programming, Simulations, Research Specific Projects

Transport
Implications for
Arctic Air quality
and Meteorology

Amir A. Aliabadi

Introduction

Atmospheric
Turbulence

Transport Modelling

Planetary

Boundary Layer (PBL)

Definition

Equations

Arctic

Case Study 1

Mixing Height (MH)

MH Models

MH Observations

Case Study 2

Turbulent Flux

Flux Models

Flux Observations

Conclusions

Closing

Closing

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Introduction

Atmospheric
Turbulence
Transport Modelling

Planetary Boundary Layer (PBL)

Definition
Equations
Arctic

Case Study 1

Mixing Height (MH)
MH Models
MH Observations

Case Study 2

Turbulent Flux
Flux Models
Flux Observations

Conclusions

Closing