Lake-Effect

Characteristics, Processes and Lake-Orographic Interactions

Atmos 6250: Mountain Meteorology

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Learning Objectives

- After this class you should be able to
  - Recognize several ways that lakes and complex terrain affect the morphology and intensity of lake-effect storms
  - Use this recognition to better analyze and predict lake-effect storms
  - Be prepared to help us advance our understanding of lake-effect storms in areas of complex terrain!

Outline

- Introduction
- The Great Salt Lake (GSL)
- The GSL-effect
  - Morphology and climatology
  - Environmental conditions
  - Shoreline band dynamics
- Orographic effects
- Japan
- Mechanisms of Orographic Enhancement

Introduction

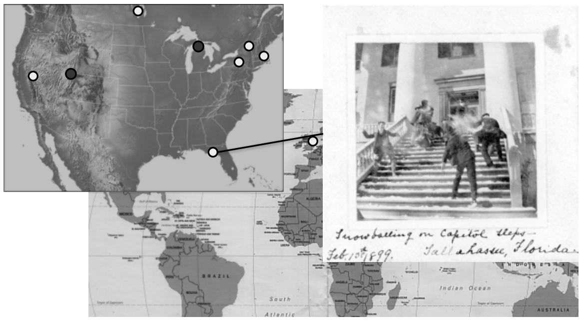
What Is Lake Effect Snow?

- "Lake effect snow is produced when cold winds move across long expanses of warmer lake water, *picking up water vapor*, which freezes and is deposited on the lee shores"
  – Wikipedia.com (2006)
- "Precipitation occurring near or downwind from the shore of a lake resulting from the *warming (destabilization) and moistening* of relatively cold air during passage over a warm body of water"
  – Glossary of Meteorology (2000)

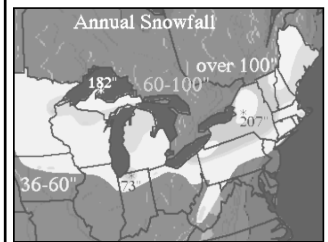
Additional Factors

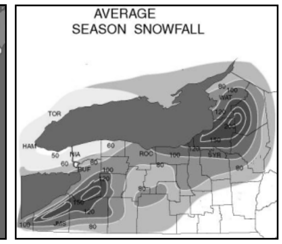
- Lake-lake interactions & aggregate effects (Great Lakes)
- Boundary layer & thermally driven circulations
- Orography
  - Mountains, hills, plateaus, and windward/leeward coastal geometry
- Surface roughness contrasts
- Ice cover

Lake-Effect Regions



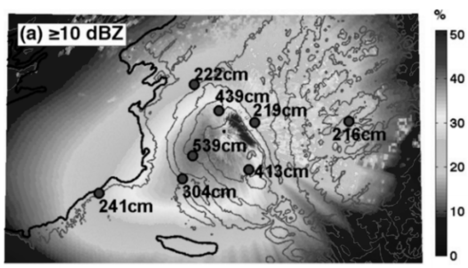
Great Lakes Climatology





University of Illinois Urbana-Champaign, National Weather Service

Lake Ontario and Tug Hill



Frequency ≥ 10 dBZ during lake-effect periods & snowfall on lake-effect days
North Redfield mean annual snowfall = 718 cm (282 inches)

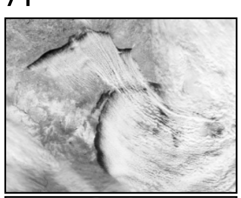
Veals and Steenburgh (2015)

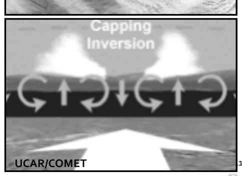
Great Lakes Snowfall Records

- 24 h: 77" @ Montague, NY
- Storm: 95" @ Montague, NY (10-14 Jan 97)
- Month: 192" @ Bennett Bridges, NY (Jan 1978)
- Winter: 466.9" @ Hooker, NY (1976-77)

Event Types

- Wide-area coverage
  - Wind parallel bands (a.k.a. cloud streets)
  - Horizontal roll convection
  - Rolls oriented along boundary layer shear vector

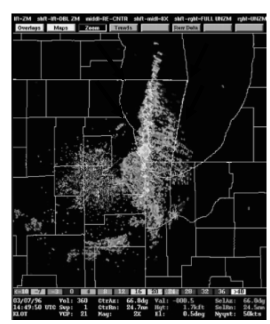




NASA, UCAR/COMET

Event Types

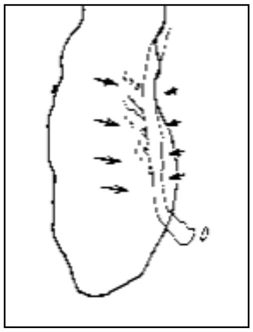
- Shore-parallel bands
  - Type I: MidLake
  - Flow along major lake axis
  - Large lake-land temperature difference
  - Land-breeze fronts form one convergence zone



Paul Markowski, Penn State University

Event Types

- Shore-parallel bands
  - Type II: Shoreline bands
  - Form near lee shore
  - Land breeze opposes large-scale flow

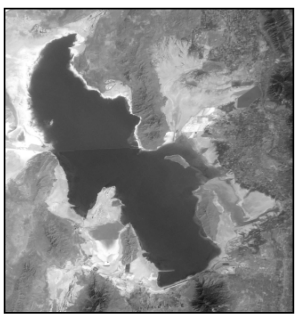


Hjelmfelt (1990)

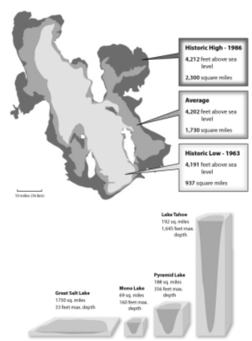
The Great Salt Lake

GSL Physiography

- Length: 120 km
  - Lake Ontario: 311 km
- Width: 45 km
  - Lake Ontario: 85 km
- Area: 2500–5900 km²
  - Lake Ontario: 19,000 km²
- Ave depth: 4.5 m
  - Lake Ontario: 86 m
- Surrounded by intense, steeply sloped mountains
  - Lake Ontario: Tug Hill (500 m above lake level)
- Salinity
  - Gilbert Bay: 6–12%
  - Gunnison Bay: 27%

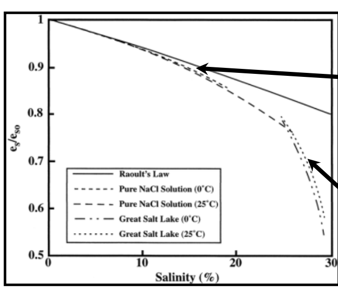


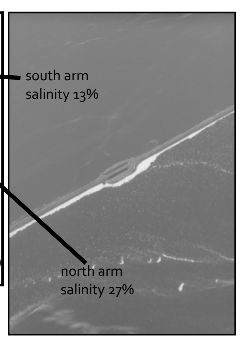
Elevation, Depth, and Area



http://learn.genetics.utah.edu/content/gsl/physical_char/

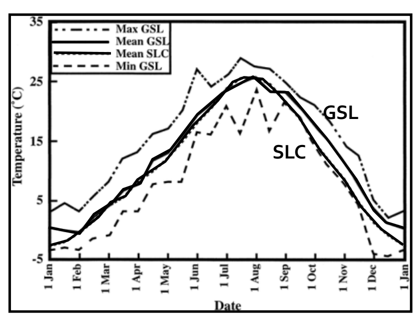
Salinity





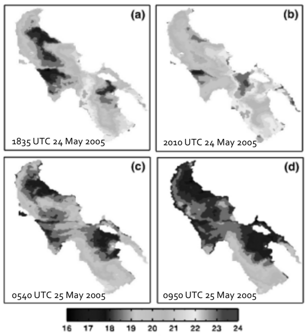
Dickson et al. (1965), Steenburgh et al. (2000)

Temperature Climatology



Steenburgh et al. (2000)

Spatio-Temporal Variability

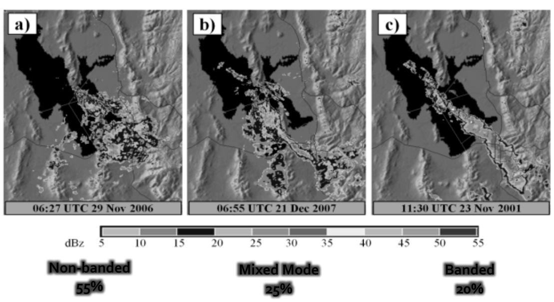


Crosman and Horel (2009)

The GSL-Effect

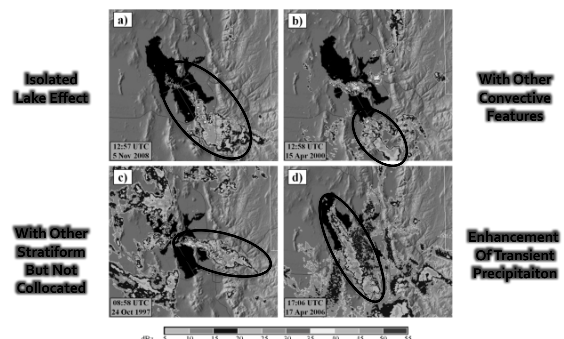
Morphology and Climatology

Morphology



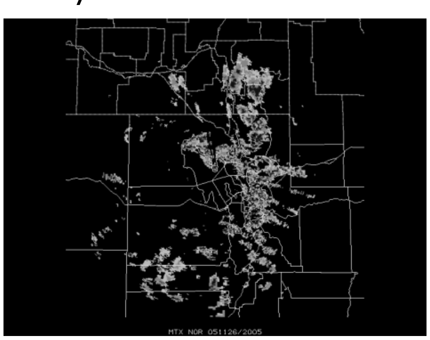
Alcott et al. (2012)

Pure and "Contaminated"

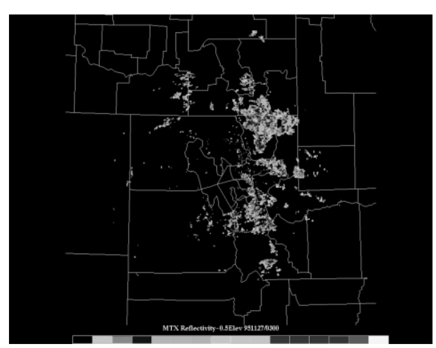


Alcott et al. (2012)

Weakly or Non Banded Event

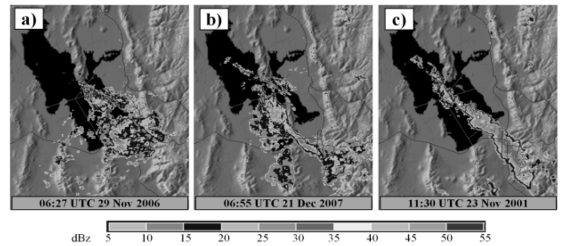


Banded Event



Cloud Band

Discussion



Non-banded
55%

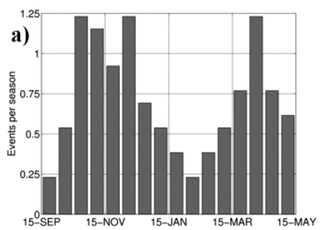
Mixed Mode
25%

Banded
20%

What controls the morphology of lake-effect systems?

Alcott et al. (2012)

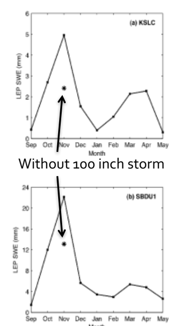
Seasonality

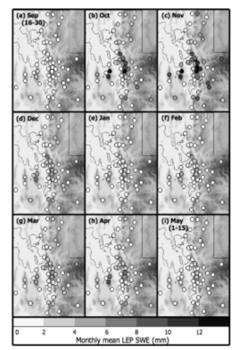


- Bimodal seasonality in event frequency
- Primary LEP SWE peak in fall

Alcott et al. (2012), Yeager et al. (2013)

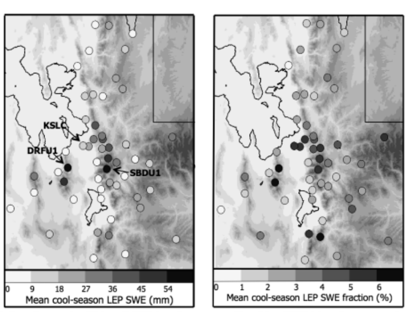
Seasonality





Yeager et al. (2013)

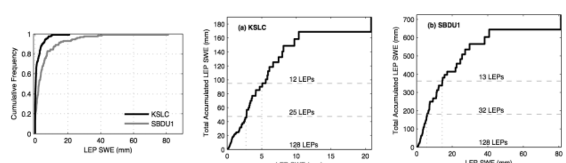
Mean Cool Season SWE



KSLC=16 mm/5.8%   DRFU1=60.1 mm/8.4%   SBDU1=60.4 mm/5.1%

Yeager et al. (2013)

Rare but Intense Events Dominate

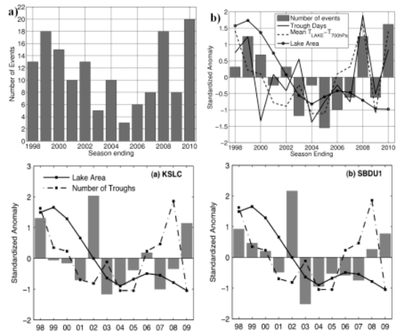


Lots of small events
> 10 mm very rare (<2%) @ KSLC
>20 mm < 5% of events @ SBDU1

12(13) events produced 50% of the LEP SWE at KSLC (SBDU1) from 1998–2009
One LEP during 100 inch storm is a real outlier

Yeager et al. (2013)

Interannual Variability



Alcott et al. (2012), Yeager et al. (2013)

The GSL-Effect

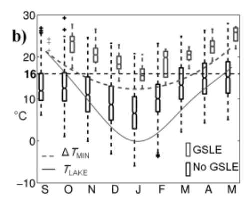
Environmental Conditions

Key Ingredients

- Instability
  - lake–700-mb ΔT>16ºC
  - 16ºC is approximately a dry adiabatic lapse rate
  - Alcott et al. (2012) show important exceptions exist
    - Events are moist and exclusively in Dec–Feb
- Upstream Moisture
- Wind Direction/Fetch
- Land-Breeze Convergence

Steenburgh et al. (2000), Alcott et al. (2012)

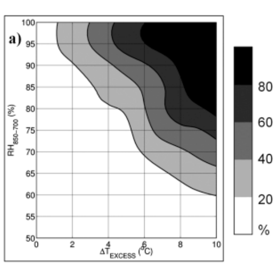
Instability



- 93% of events occur at lake–700-mb ΔT≥16ºC
  - Exceptions occur exclusively during winter months ("moist" events)
  - Fall and spring events occur at higher thresholds
  - Suggests a seasonally varying threshold (ΔT_{excess}) is more appropriate than a fixed threshold

Alcott et al. (2012)

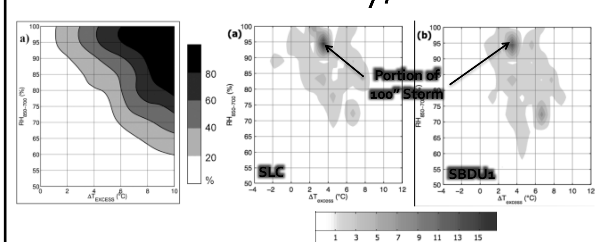
Moisture



Fraction of soundings with GSLE as a function of (ΔT_{excess}) and 850–700-mb RH
Moisture matters, avoid "thermomyopia"

Alcott et al. (2012)

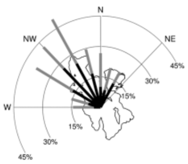
More on Instability/Moisture



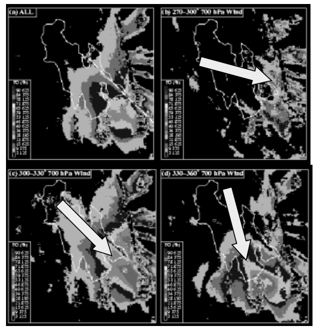
Event intensity/LEP SWE not well correlated with Δt_{excess} and moisture
Other processes, poorly resolved by current obs and analyses, are likely important

Alcott et al. (2012), Yeager et al. (2013)

Wind Direction/Fetch

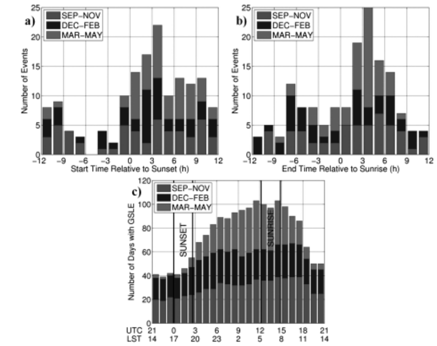


Fraction of soundings with GSLE vs. 700-mb wind direction &



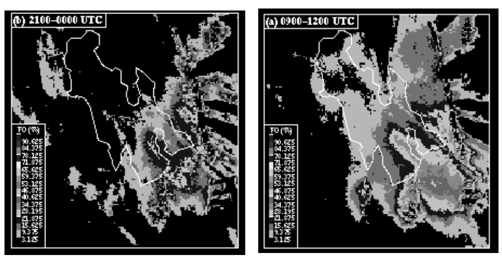
Alcott et al. (2012), Steenburgh et al. (2000)

Diurnal Variability



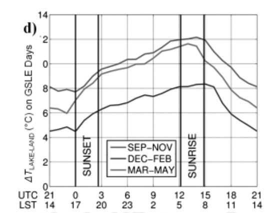
Alcott et al. (2012)

Diurnal Variability

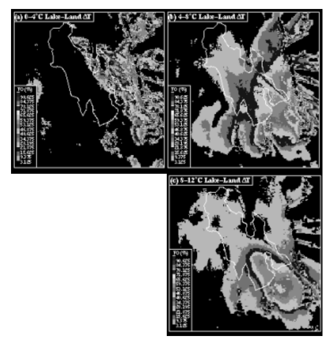


Steenburgh et al. (2000)

Lake–Land ΔT



Diurnal variability & seasonality



Steenburgh et al. (2000), Alcott et al. (2012)

Discussion

Why is the correlation between environmental conditions and the occurrence and intensity of lake-effect so limited?

What does this mean for weather prediction?

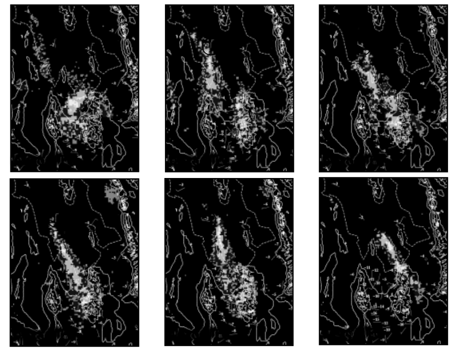
The GSL-Effect

Shoreline Band Dynamics

7 December 1998 Event

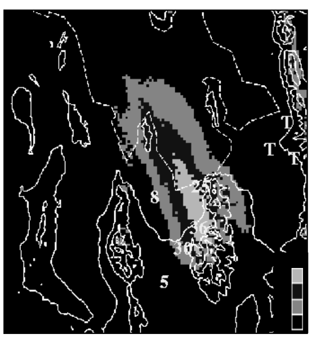
- Two lake-effect snowbands merged into a shoreline band
- Heaviest snow (up to 36 cm) concentrated in a narrow, 10-km wide band over Tooele County

Mesoscale Evolution



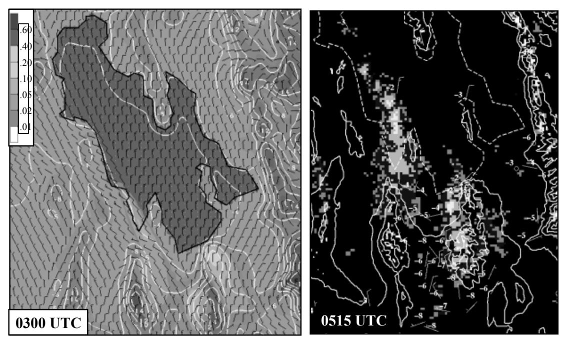
Steenburgh and Onton (2001), Onton and Steenburgh (2001)

Total Snowfall (cm)



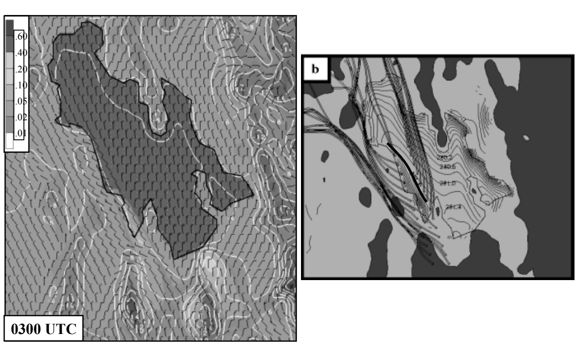
Steenburgh and Onton (2001), Onton and Steenburgh (2001)

Initiation Phase



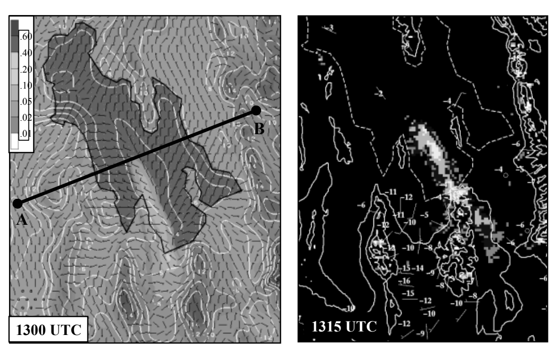
Steenburgh and Onton (2001), Onton and Steenburgh (2001)

Initiation Phase



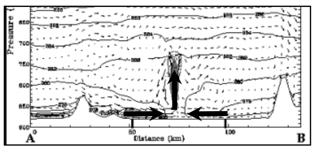
Steenburgh and Onton (2001), Onton and Steenburgh (2001)

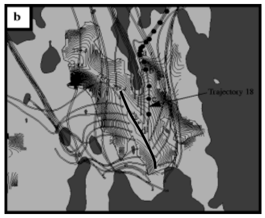
Mature Phase



Steenburgh and Onton (2001), Onton and Steenburgh (2001)

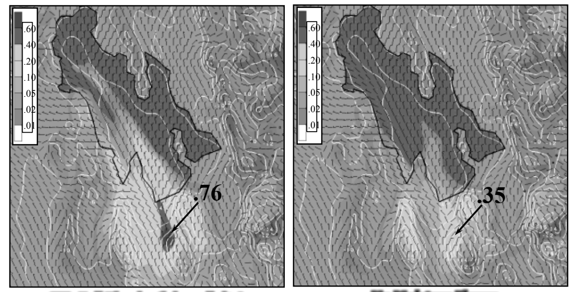
Mature Phase





Steenburgh and Onton (2001), Onton and Steenburgh (2001)

Moisture Flux Sensitivity

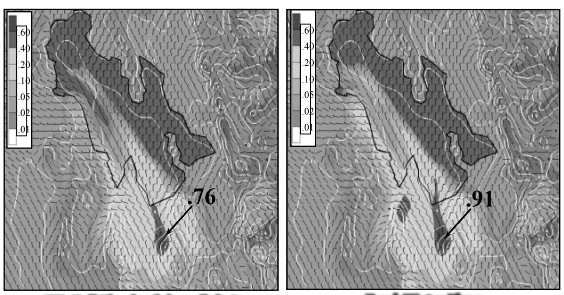


CTL-Full Physics (lake salinity) **No Moisture Fluxes**

49% less domain-wide precipitaiton without moisture fluxes

Steenburgh and Onton (2001), Onton and Steenburgh (2001)

Moisture Flux Sensitivity



CTL-Full Physics (lake salinity) **Fresh Water Fluxes**

20% more domain-wide precipitaiton in freshwater simulation

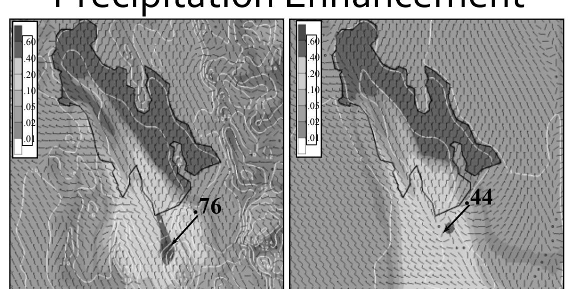
Steenburgh and Onton (2001), Onton and Steenburgh (2001)

Orographic Effects

Potential Orographic Effects

- Precipitation enhancement
- Modification of the lake-effect system
  - Initiation, intensity, morphology
- Lake-effect systems can be altered by upstream and downstream topography

Precipitation Enhancement



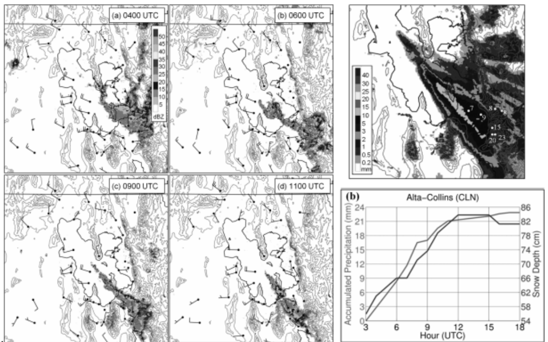
CTL-Full Physics (lake salinity) **No Topography**

Lake-dominated system

Enhancement within band, but no major impact on initiation or morphology

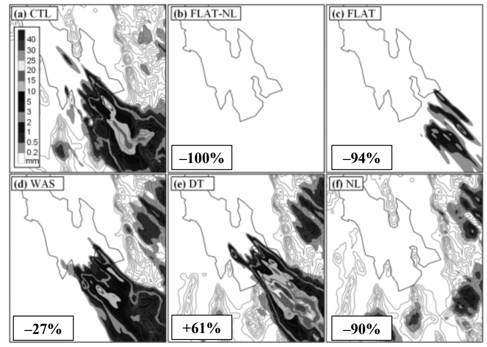
Steenburgh and Onton (2001), Onton and Steenburgh (2001)

System Modification: 27 Oct 2010



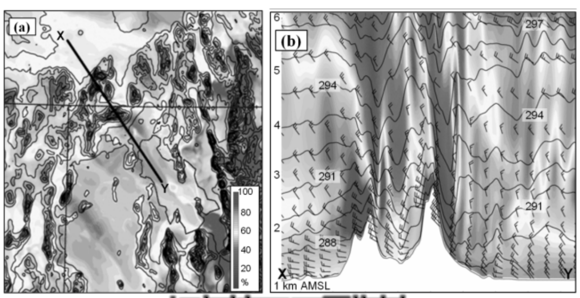
Alcott and Steenburgh (in prep)

Terrain Sensitivity



Alcott and Steenburgh (in prep)

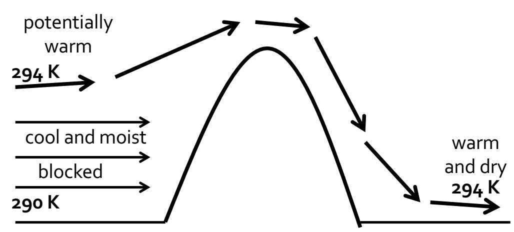
Upstream Influences



Low-level airmass over SRP blocked
Foehn-like warming and drying of air moving over GSL-bason

Alcott and Steenburgh (in prep)

Upstream Influences



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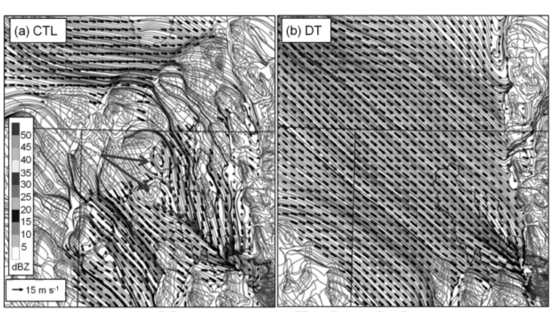
Alcott and Steenburgh (in prep)

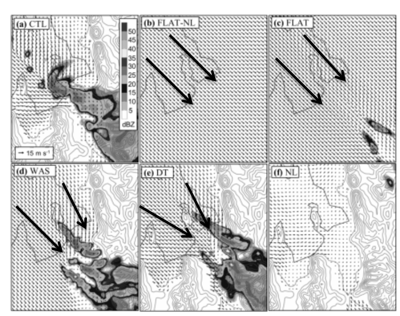
Upstream Influences



Overlake convergence and band organization

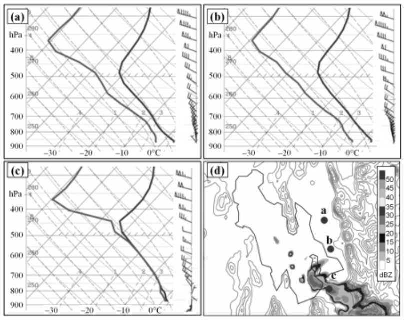
Alcott and Steenburgh (in prep)

Downstream Influences



Alcott and Steenburgh (in prep)

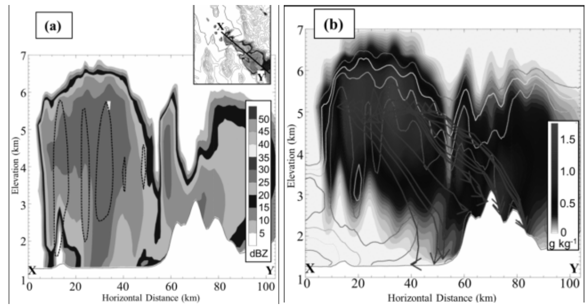
Blocking



Stable to dry motions in area around GSL

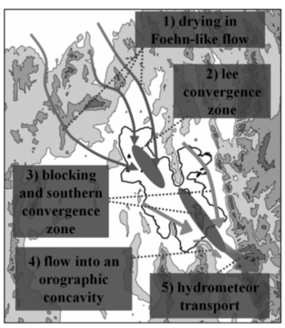
Alcott and Steenburgh (in prep)

Microphysical Considerations



Alcott and Steenburgh (in prep)

27 Oct 2010 Summary



Alcott and Steenburgh (in prep)

Discussion

7 Dec 1998

27 Oct 2010

Lake Dominated

Orographic Dominated

Little sensitivity to the presence of the GSL

What controls the relative contribution of lake and orographic effects on lake-effect systems?

Why are some events "lake dominated"?
Why are others influenced strongly by lake-orographic interactions?

Japan

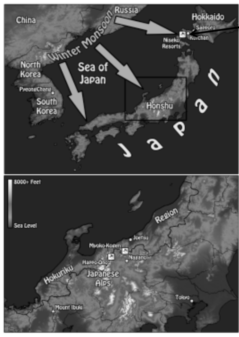
Hokuriku District

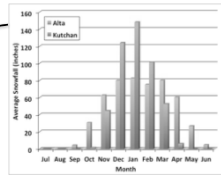
Joetsu, Hokuriku District
Elevation: sea level
Population: 205,000
Annual SWE: 108" (276 cm)
Annual Snow: 248" (630 cm)
Record Snow: 590" (1499 cm)

Probably the snowiest urban area in the world

Steenburgh (2014), GoogleEarth, JMA via Wikipedia

Hokkaido Island





Kutchan, Hokkaido Island
Elevation: 180 m
Population: 15,000
Annual Snow: 480" (1220 cm)

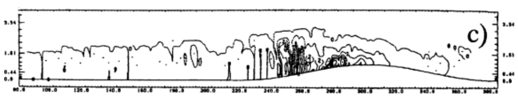
Probably the snowiest near-sea-level location in the world

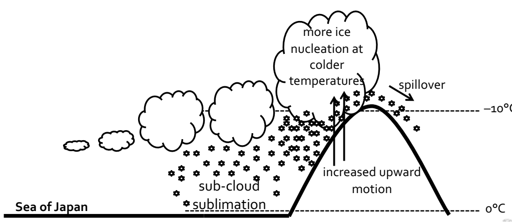
Steenburgh (2014), JMA via Wikipedia

Mountains

Steenburgh (2014), http://www.jnto.go.jp/tourism/en/s007.html

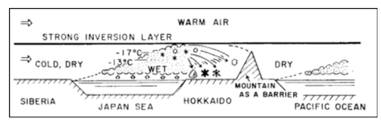
Orographic Enhancement





Saito et al. (1996)

Importance of the CAP



<u>CAP</u>=Capping Inversion or Stable Layer

<u>Satoyuki Storms</u>: Produce more snow in the coastal lowlands
<u>Yamayuki Storms</u>: Produce more snow in the mountains

<u>Hypothesis</u>: Height of CAP relative to mountain crest affects orographic ratio in lake-effect storms

Magono et al. (1966)

Mechanisms of Orographic Enhancement

Conventional Wisdom

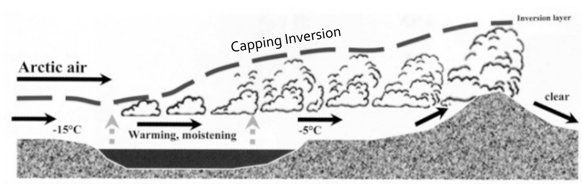
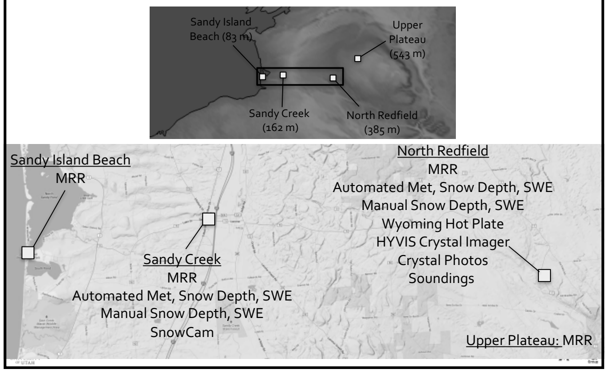


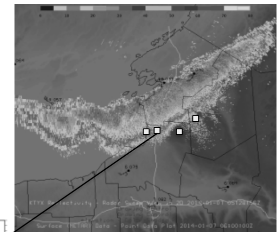
Figure 9.21. Idealized cross-sectional schematic of LES development, with downstream orographic lift. Depth of the inversion along the flow shown as a dashed red line.

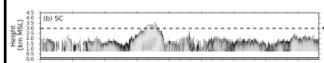
Orographic lifting invigorates convection
(i.e., larger updrafts speeds and cloud depths)
Lackmann (2011)

OWLeS Orographic Transect



MicroRainRadars (MRRs)

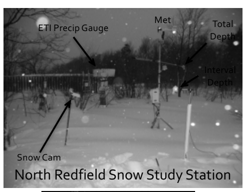


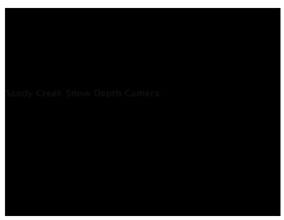


IOP7 Thundersnow
24 lightning flashes 0630–1120 UTC
Surface Temps -10 to -19ºC

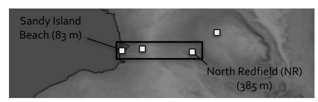
Snow and Water Equivalent Obs

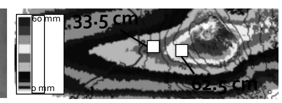
Collected @ Sandy Creek (lowland, 162 m MSL) and North Redfield (upland, 385 m MSL)

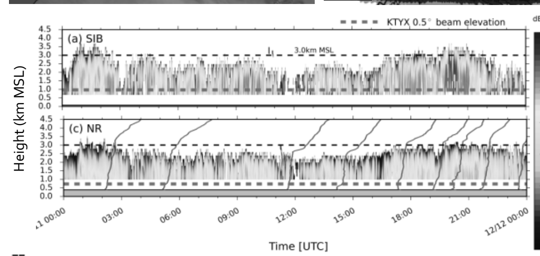




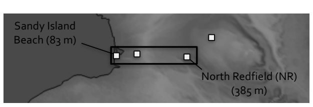
IOP2: MRRs

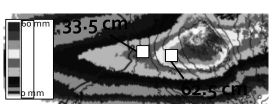


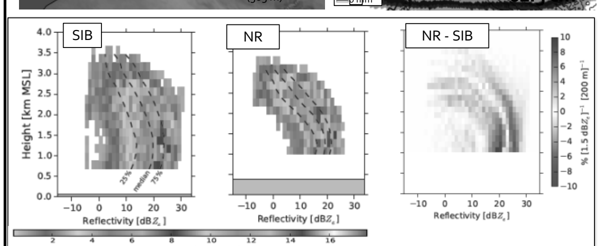




IOP2 CFADs

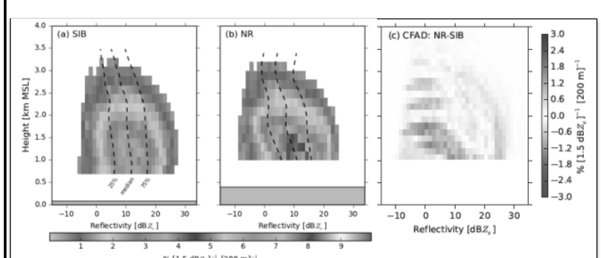






SIB –> NR: Echoes shallower, more consistent (narrower IQR), and more frequent near ground

All 29 Events @ SIB & NR



Conventional Wisdom

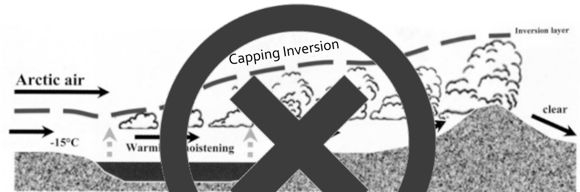


Figure 9.21. Idealized cro ctional schematic of LES de ment, with downstream orographic lift. Depth of the in on along the flow sho a dashed red line.

Orographic I convection
Lackmann (2011)

Overall enhancement: See Minder et al. 2015, http://dx.doi.org/10.1175/MWR-D-15-0117.1
OR variations: See Leah Campbell's talk next

Summary

- Many processes influence lake-effect systems
  – Upstream instability and moisture
  – Lake conditions (surface temperature, sub-surface temperature, salinity, ice cover)
  – Land breezes and PBL circulations
  – Orography

- Orographic influences not only include precipitation enhancement, but also the initiation, intensity, and morphology of lake-effect systems

Unresolved Issues

- Morphological controls
- Role of the CAP in modulating orographic enhancement
- Mechanisms of orographic enhancement
- Understanding (and predicting) the spectrum of lake-driven and terrain-driven processes that influence lake-effect storms in areas of complex terrain
- GSL: Interdecadal variability & lake size

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