Lake- and Sea-Effect Precipitation

Atmos 5210: Synoptic Meteorology II

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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

Discussion

What is lake- and sea-effect precipitation/snow?

What Is Lake- and Sea-Effect Precip?

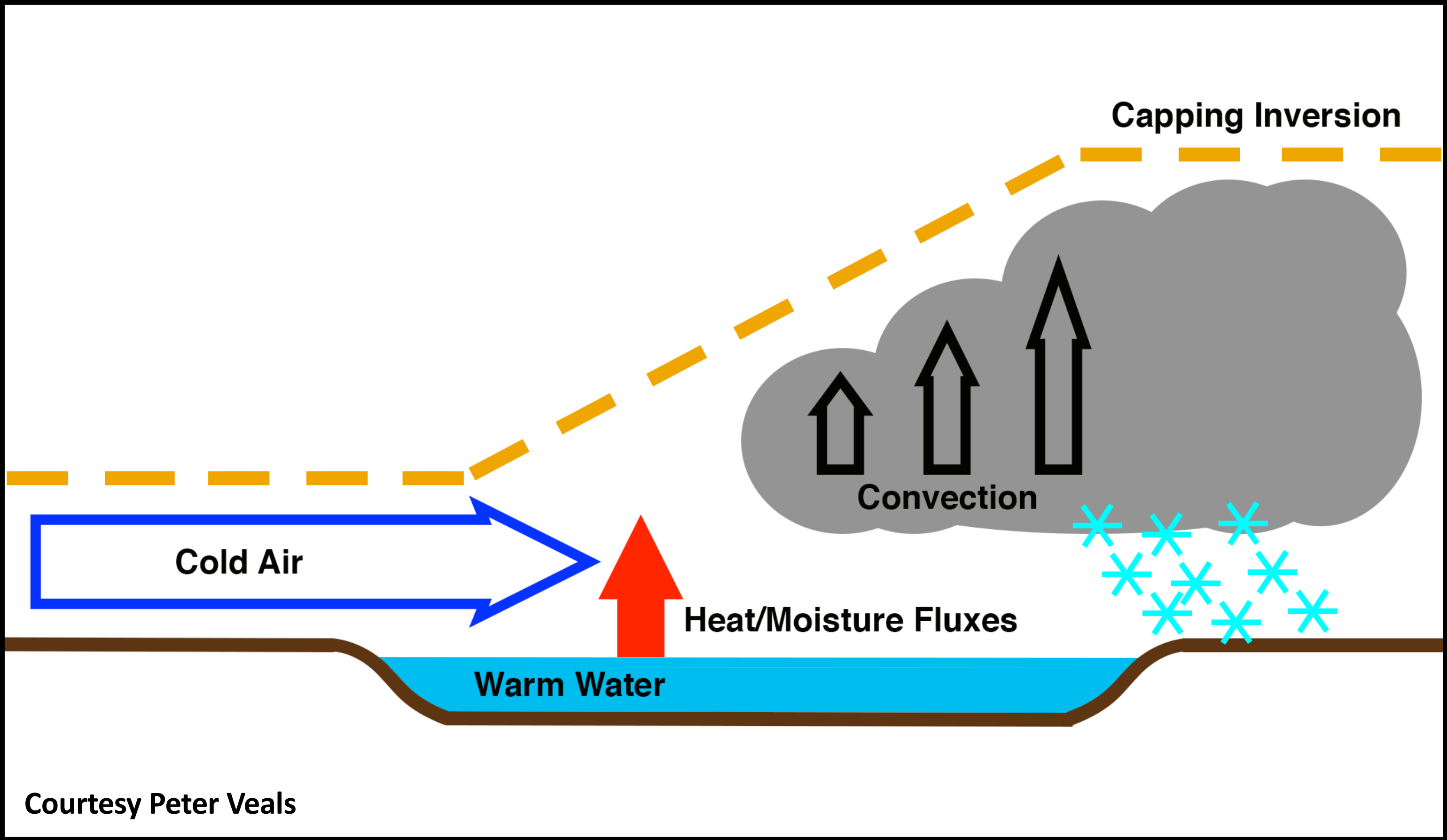
- "Lake effect snow is produced when cold winds move across long expanses of warmer lake water, *picking up water vapor,* which freezes and is deposited on the lee shores."

  – 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)

Lake- and Sea-Effect Precipitation



Precipitation produced primarily by boundary layer convection that is generated, enhanced, and organized by sensible and latent heat fluxes and associated boundary layer and mesoscale circulations as cold air moves over relatively warm water

Key Ingredients

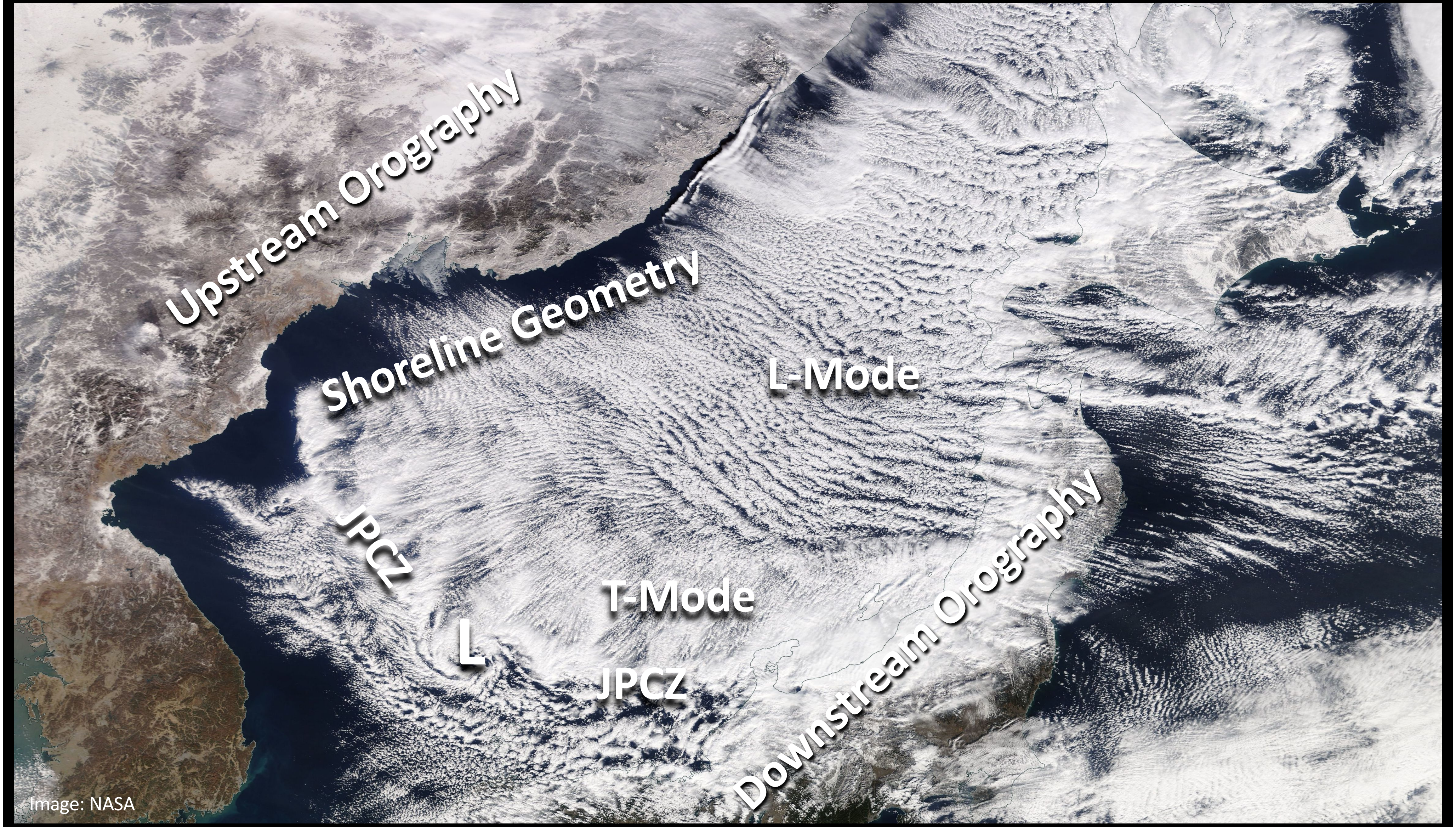
- Instability
  - Lake–850-hPa or Lake–700-hPa ΔT exceeding dry adiabatic
    - There are some exceptions
- Wind Direction/Fetch
- Moisture if fetch is small can be important
  - Less important for large bodies of water
- Boundary layer or mesoscale circulations
  - Former include land breezes and terrain-forced flows

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

Additional Factors

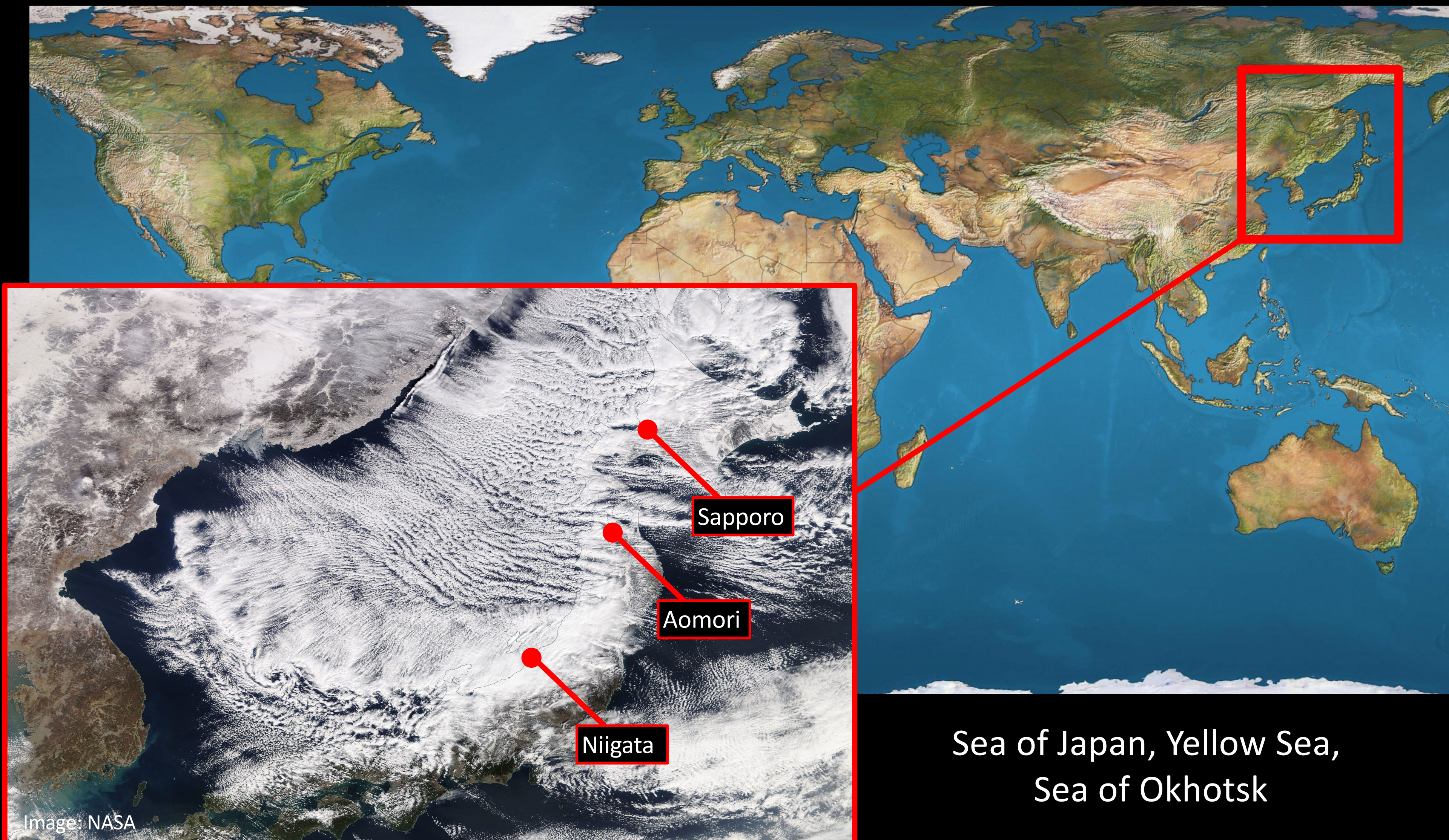
- Shoreline geometry
- Land and lake breezes
- Upstream and downstream topography
- Multi-lake/sea effects
- Ice cover (where and when it happens)

Example



Upstream Orography
Shoreline Geometry
L-Mode
JPCZ
T-Mode
L
JPCZ
Downstream Orography
Image: NASA

Lake- and Sea-Effect Regions

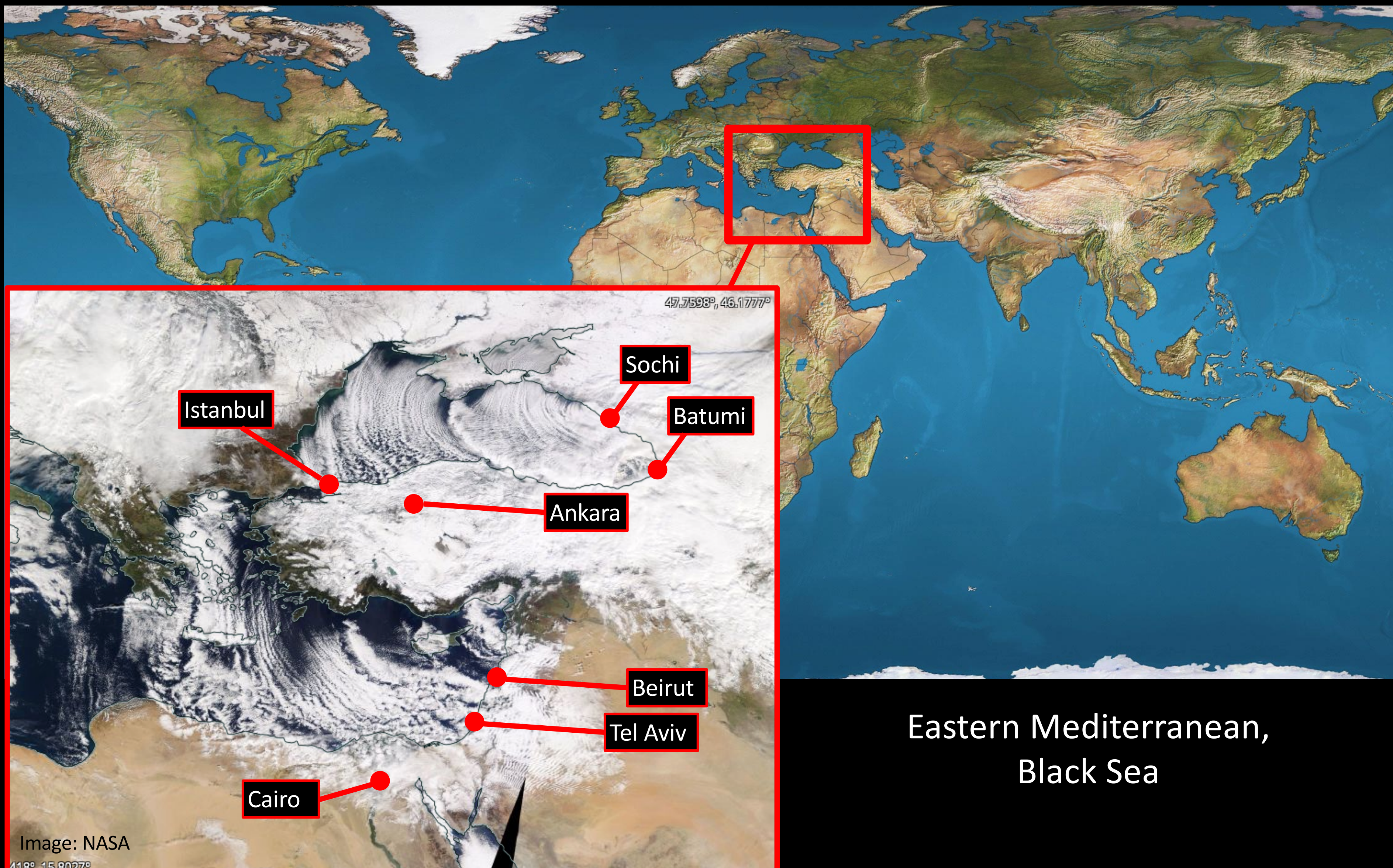


Sea of Japan, Yellow Sea,
Sea of Okhotsk

Lake- and Sea-Effect Regions

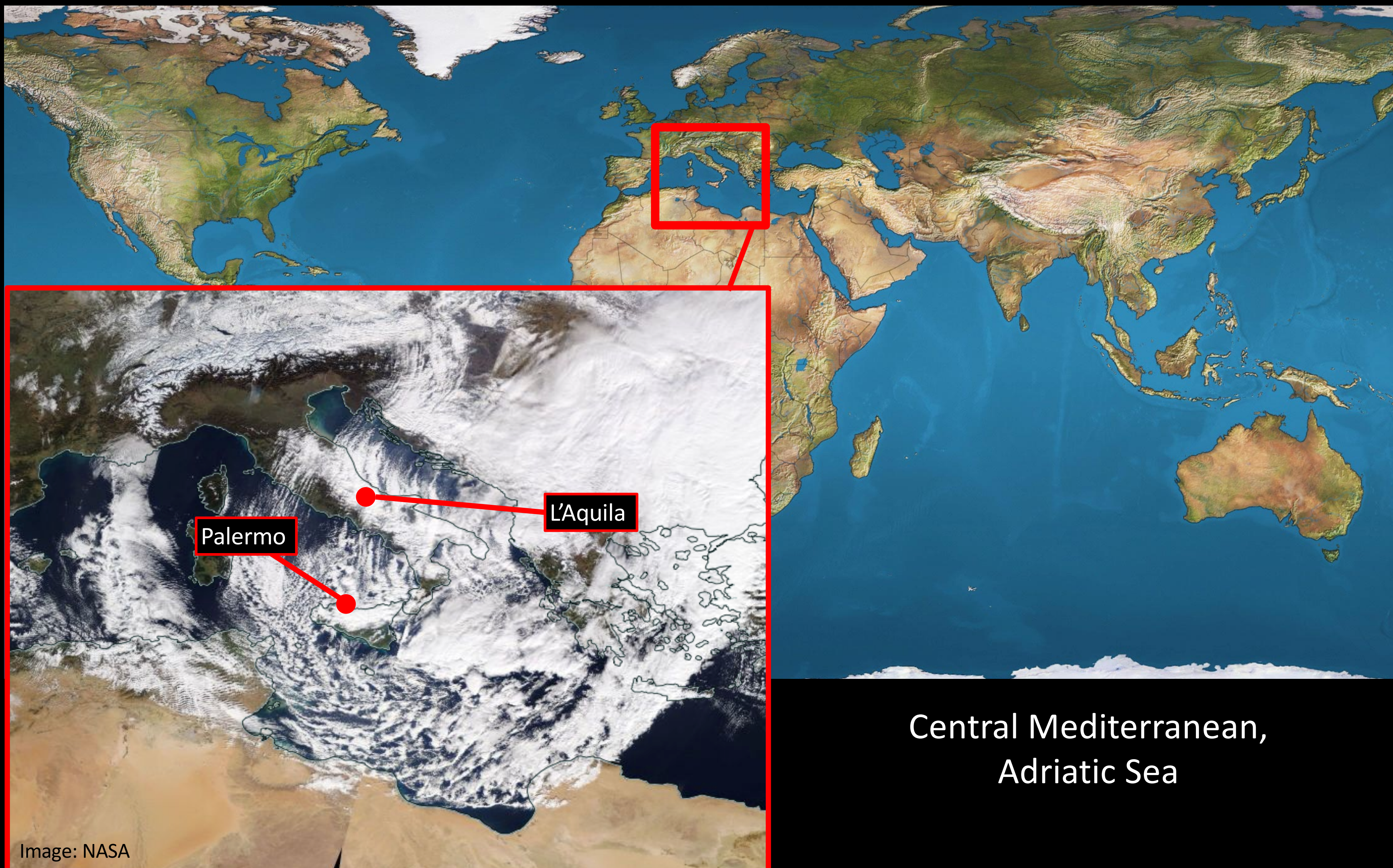
Baltic Sea, North Sea,
English Channel, Norwegian Sea

Lake- and Sea-Effect Regions



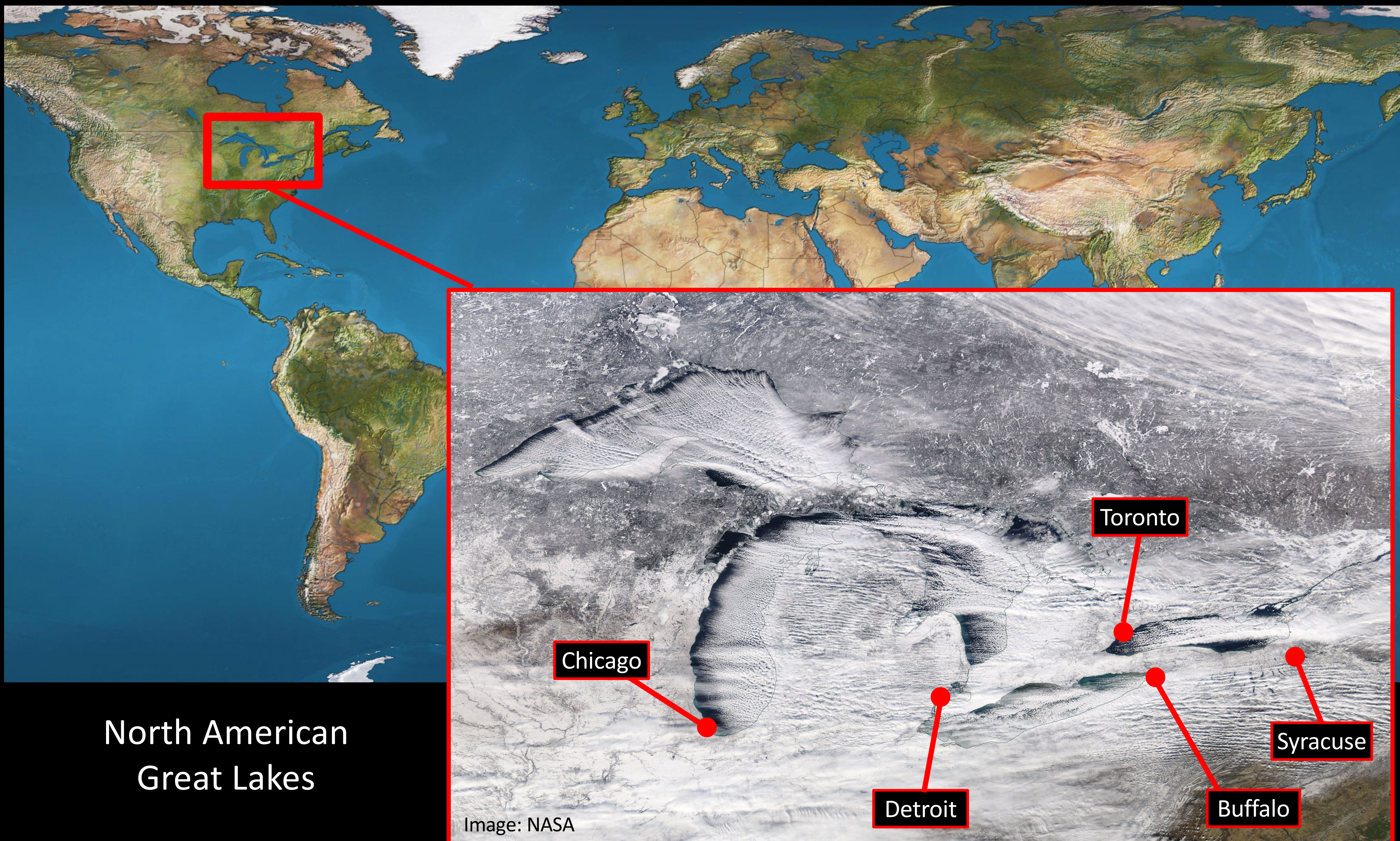
Eastern Mediterranean,
Black Sea

Lake- and Sea-Effect Regions



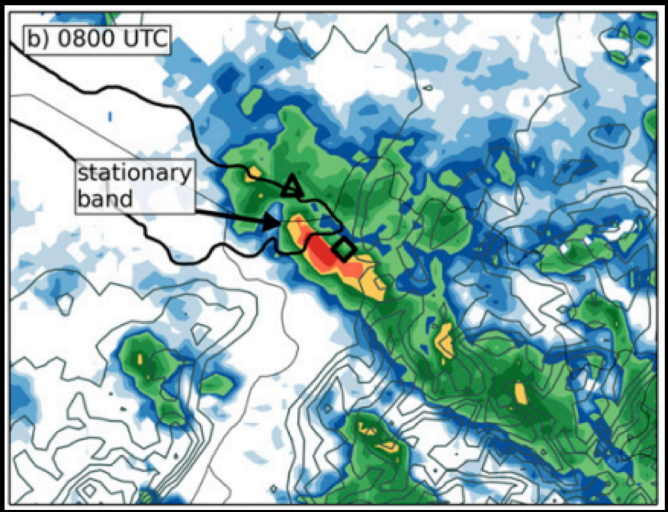
Central Mediterranean,
Adriatic Sea

Lake- and Sea-Effect Regions

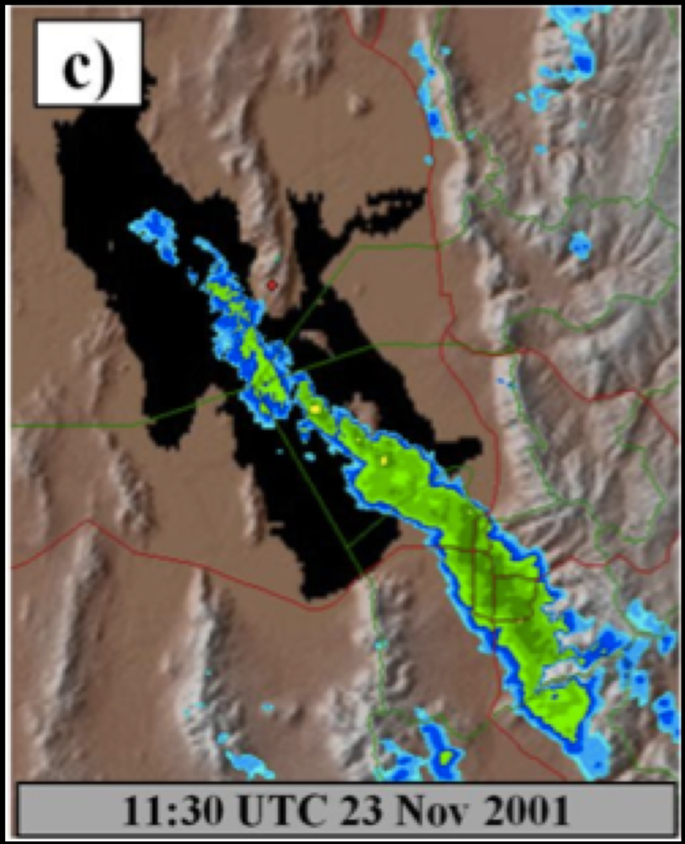


North American
Great Lakes

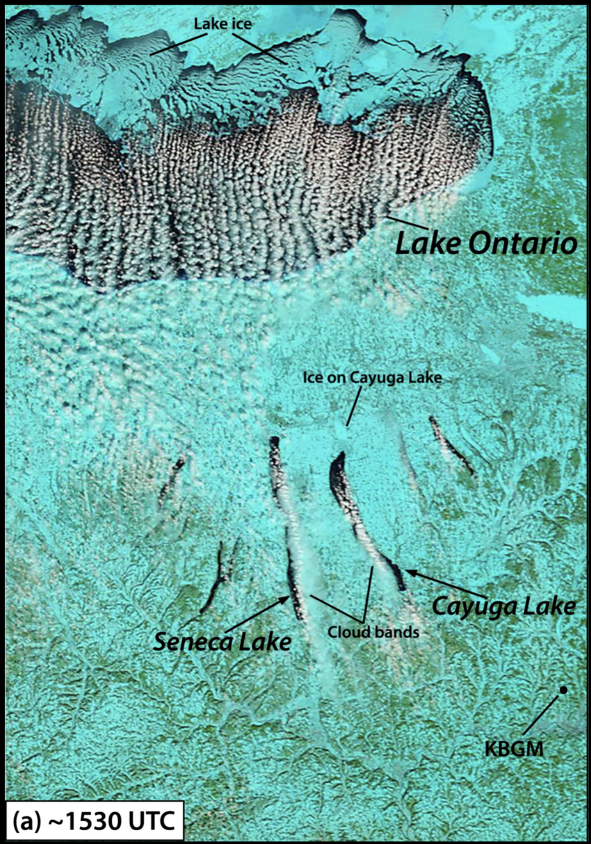
“Small” Lakes



Lake Constance, CH/DE/AT



Great Salt Lake, USA



Finger Lakes, USA

Umek and Gohm 2016; Alcott et al. 2012; Bergmaier and Geerts 2016

Extremes

<u>Lake Ontario & Tug Hill Plateau</u>

Elongated body of water 300 km long

Tug Hill Plateau rises 500 m above lake level

<u>Sea of Japan and Japanese Mountains</u>

Large body of water with NW fetch ~850 km

Downstream terrain rises ~1000–2800 m

Tug Hill: Storms of Great Intensity

“Snow rates during some events are the greatest ever measured on record from anywhere in the world”
– Burt (2007)

35 cm in 1 hour
Copenhagen, NY
2 Dec 1966

130 cm in 16 hours
Bennetts Bridge, NY
17-18 Jan 1958

196 cm in 24 hours*
Montague, NY
11-12 Jan 1997

*Based on 6 measurements

Overnight Snowfall, Adams, New York, USA
OWLeS IOP7

Burt (2007)

Tug Hill Maximum

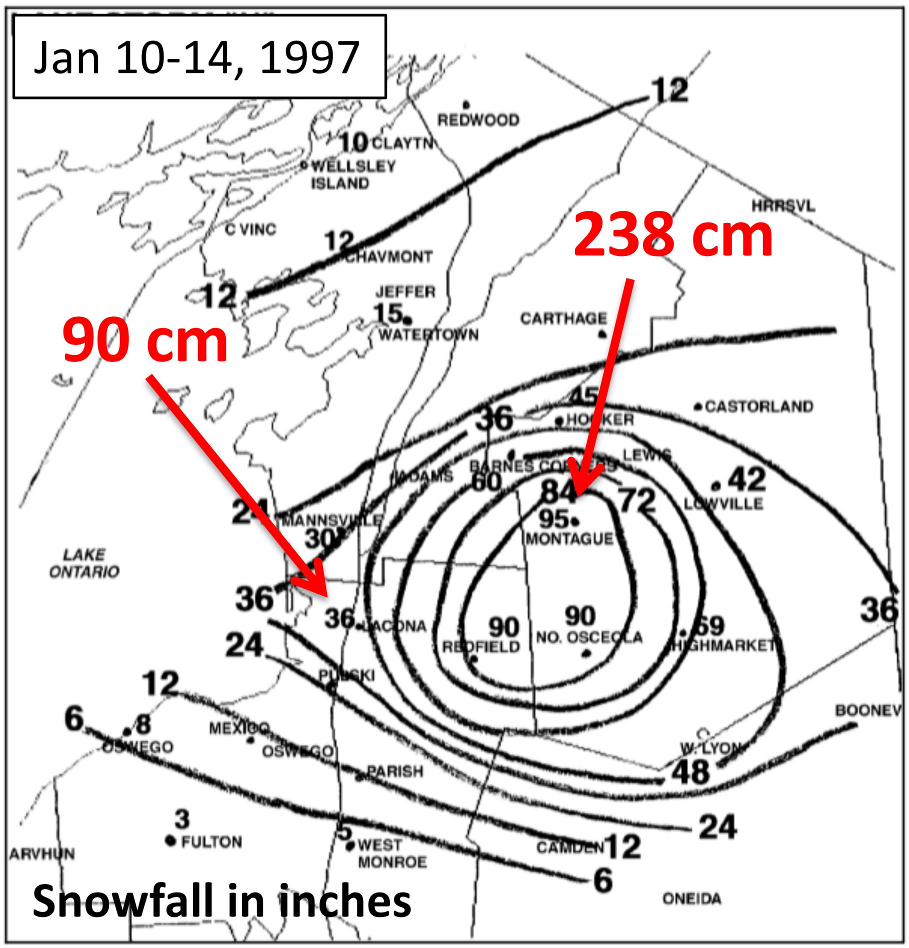
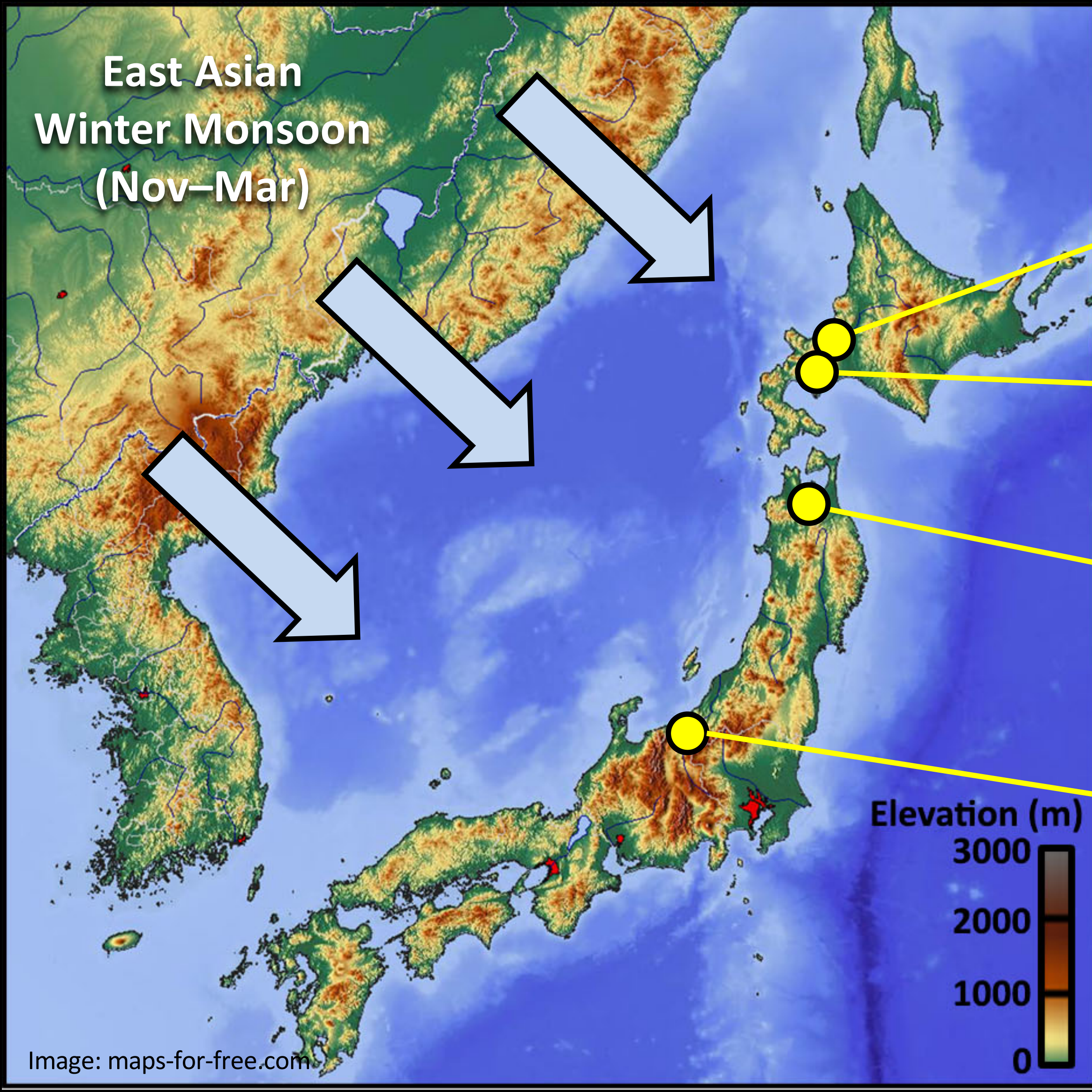


Figure 2: WSFO BUF Internet Snowfall Map for January 10-14, 1997 Tug Hill Snowstorm (date shown in upper left corner of Internet map is incorrect).

Leffler et al. (1997)

Japan’s Gosetsu Chitai (Heavy Snow Region)



Japan's Gosetsu Chitai (Heavy Snow Region)

Photo: J. Steenburgh

"The surest climatological bet for deep powder skiing anywhere in the world"

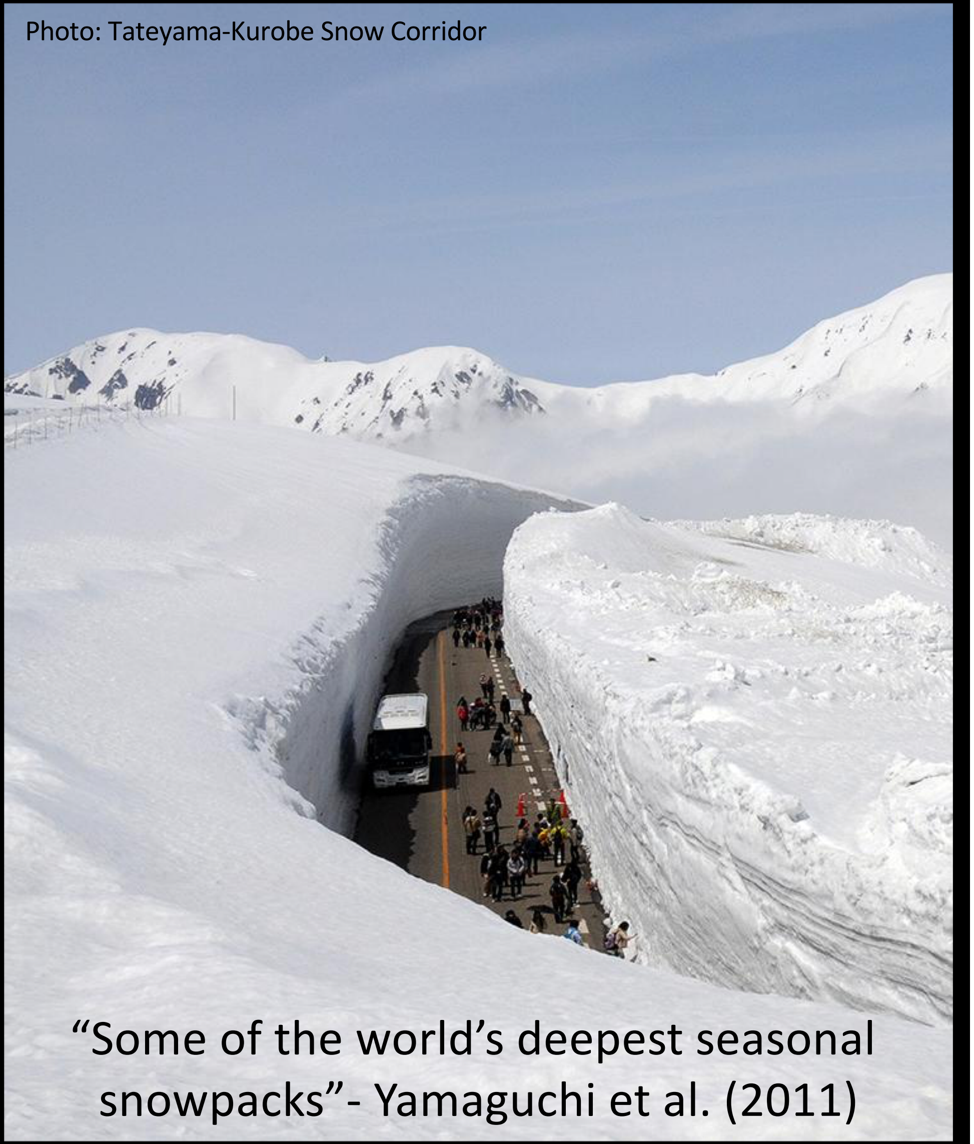


Photo: Tateyama-Kurobe Snow Corridor

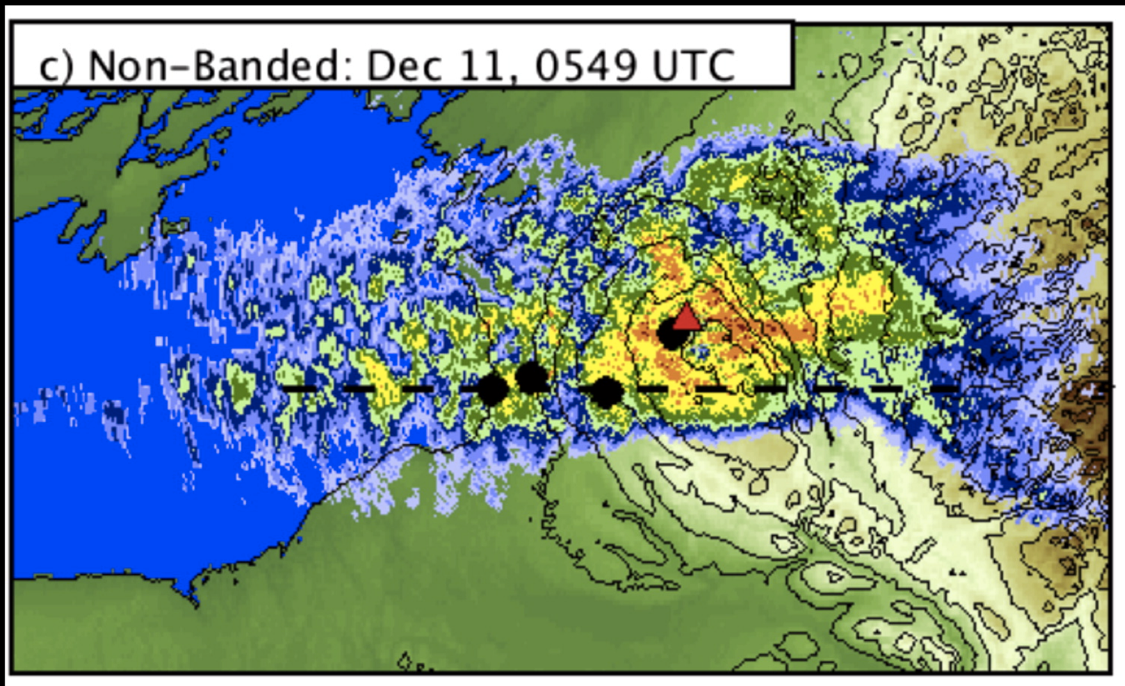
"Some of the world's deepest seasonal snowpacks"- Yamaguchi et al. (2011)

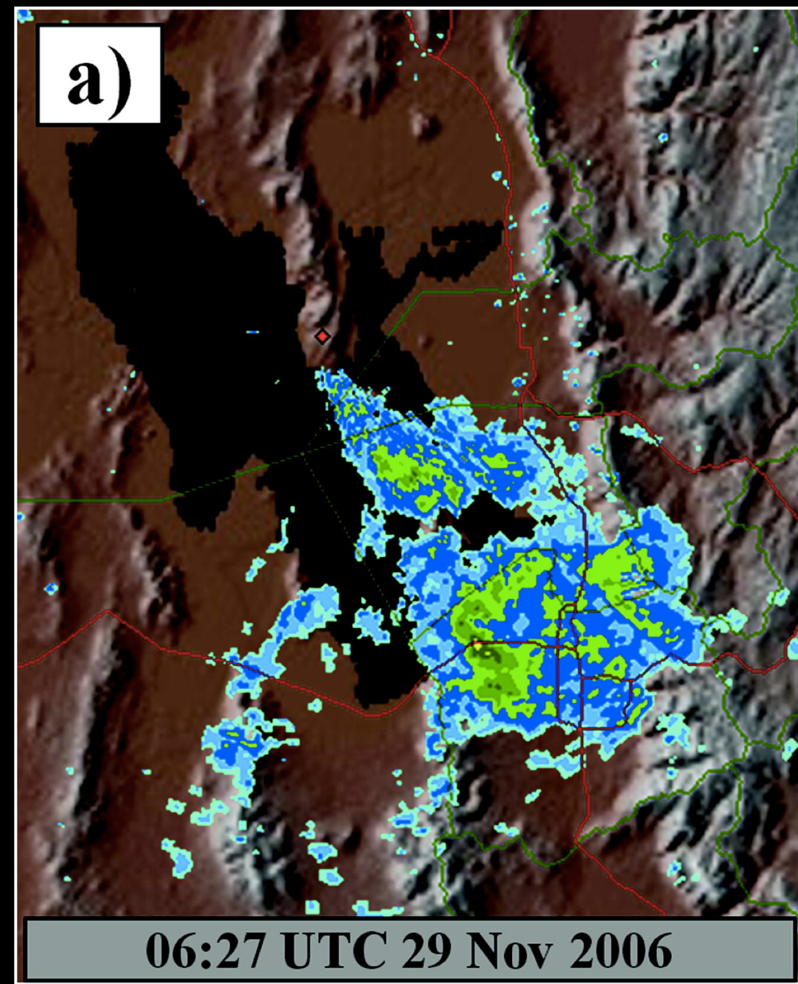
Morphology

Lake- and sea-effect modes

- "Broad coverage"
  - Open cells/non-banded
  - Longitudinal-mode bands
  - Transverse-mode bands
- Mesoscale bands
  - Long-lake-axis parallel (LLAP)
  - Japan Sea Polar Airmass Convergence Zone
  - Other terrain/coastally forced
- Mesoverticies

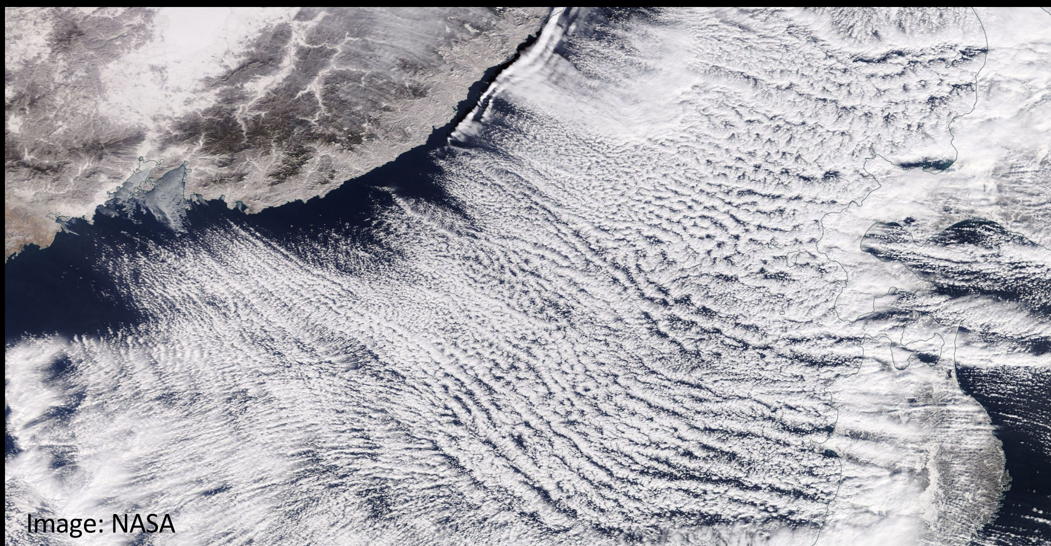
Open Cells/Non-Banded

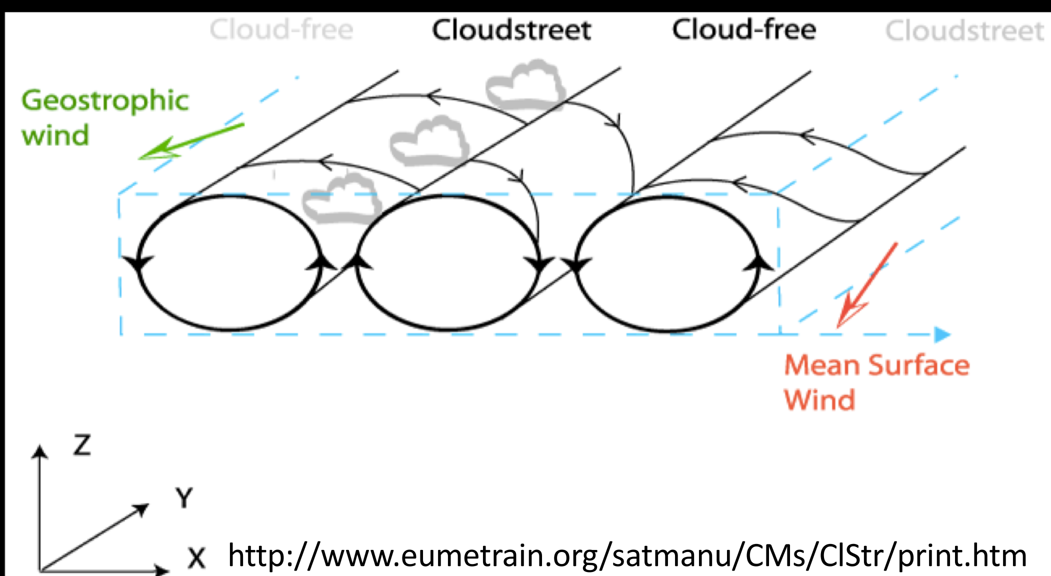




Alcott et al. 2012; Campbell et al. 2016

Longitudinal Mode (Cloud Streets)



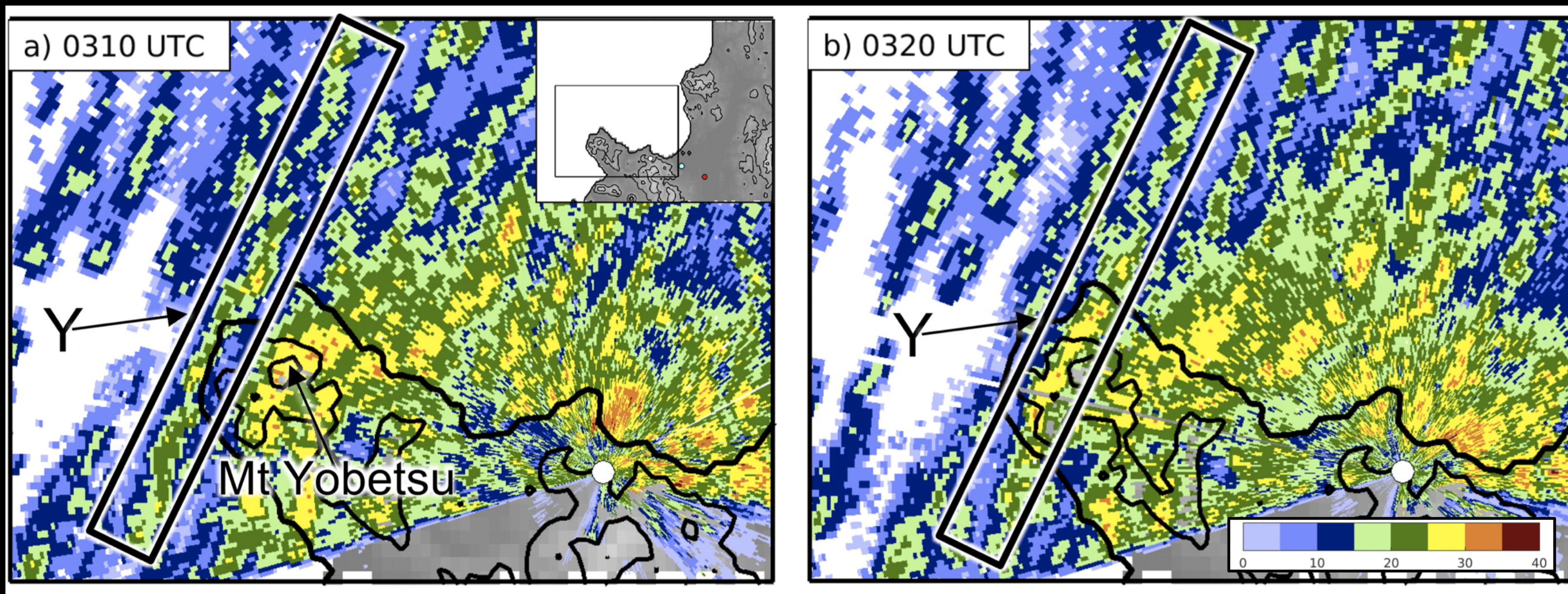


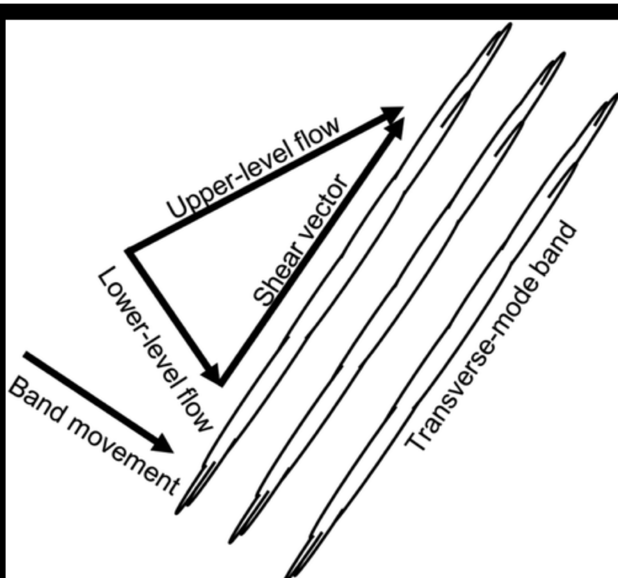
Horizontal Roll Convection

Formed by buoyancy and shear

Nearly parallel to ambient flow

Transverse Mode





Horizontal Roll Convection

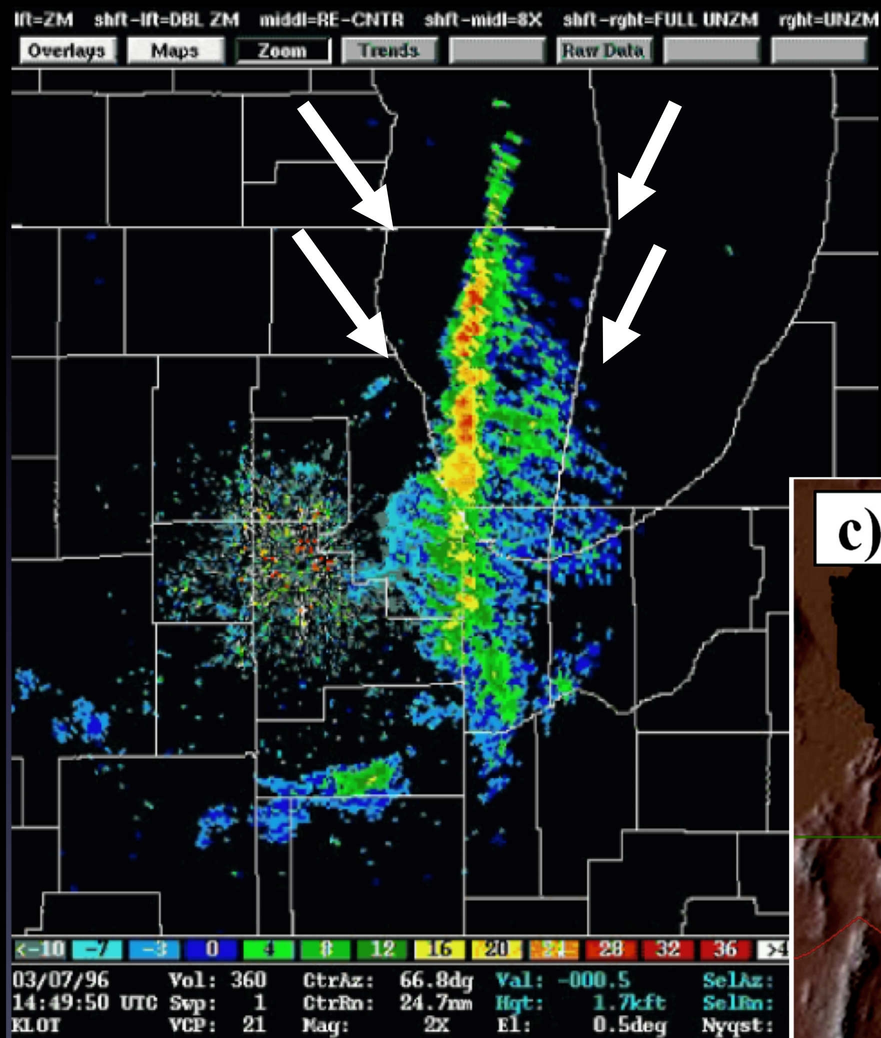
High directional shear environments

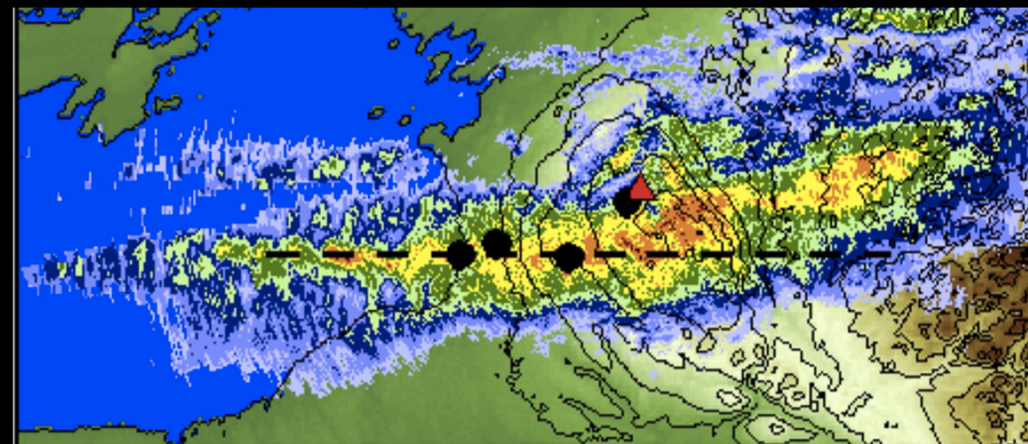
Parallel to shear vector

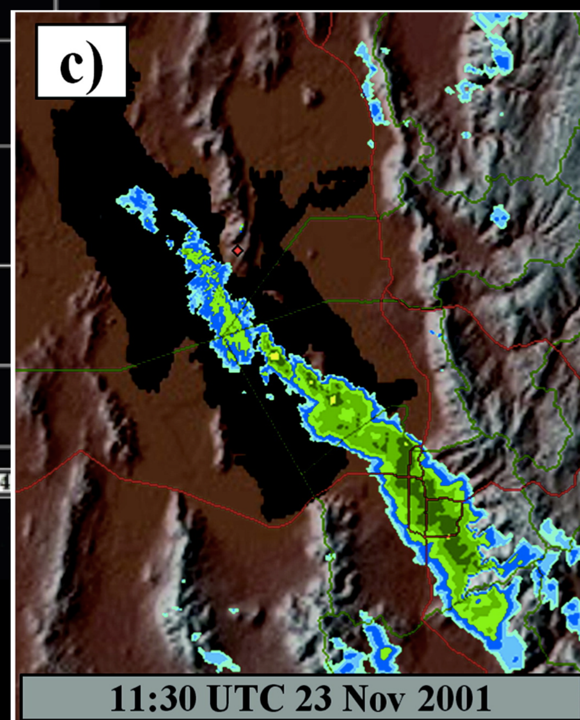
Nearly transverse to mean flow

Asai 1972; Campbell et al. 2018

LLAP Bands (Type I)







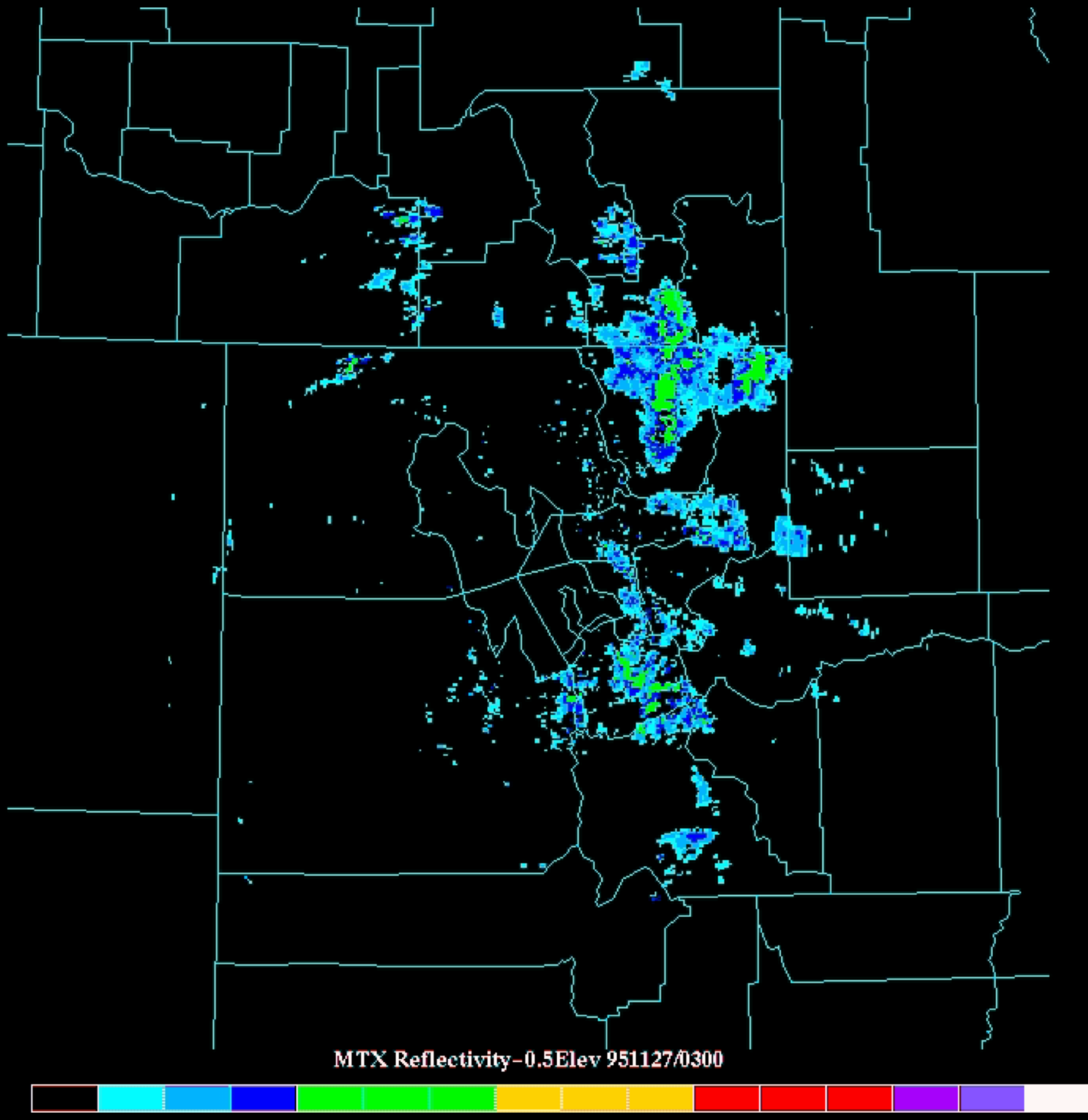
Flow along major lake axis

Large lake-land ΔT

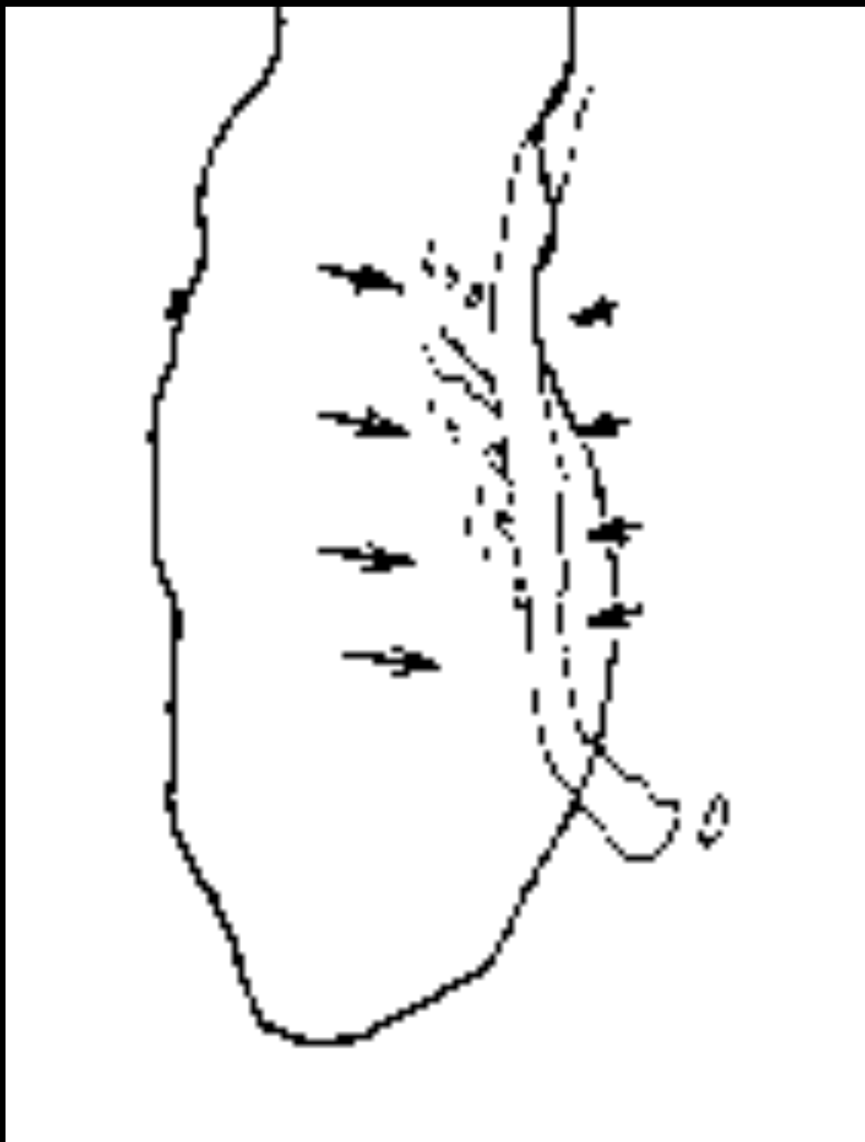
Mesoscale forcing from land breeze or breezes

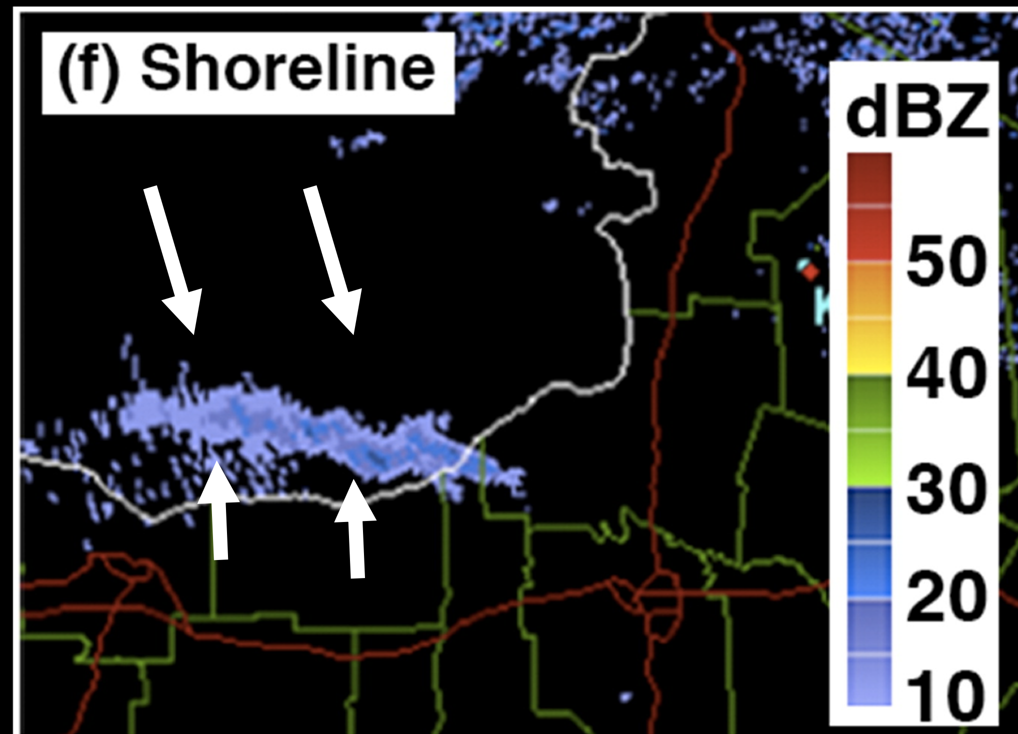
Paul Markowski; Alcott et al. 2012; Campbell et al. 2016

LLAP Band (Type I) Event



LLAP Bands (Type II)



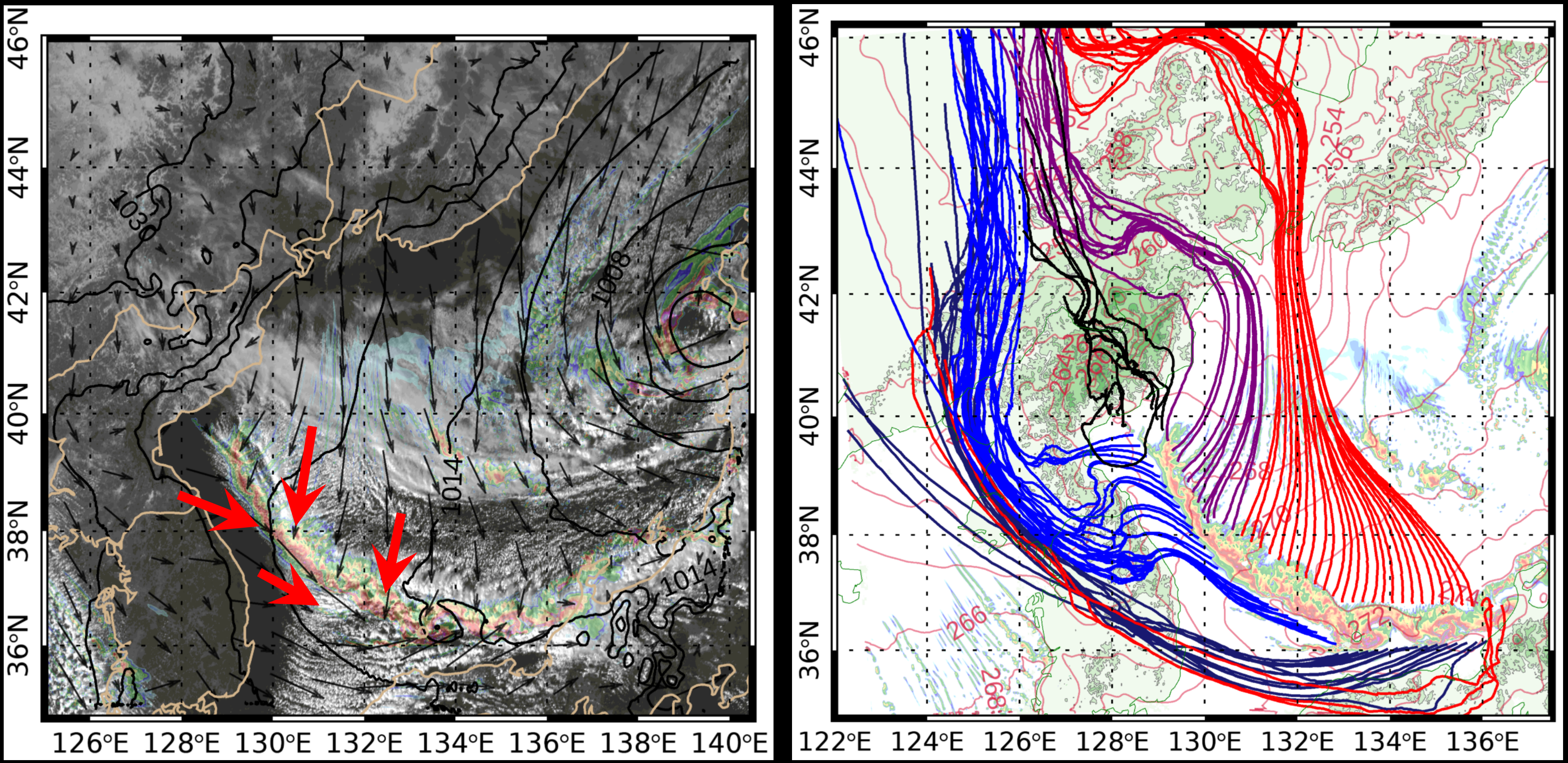


Form near lee shore

Land breeze opposes large-scale flow

Veals and Steenburgh 2015; Hjelmfelt 1990

JPCZ



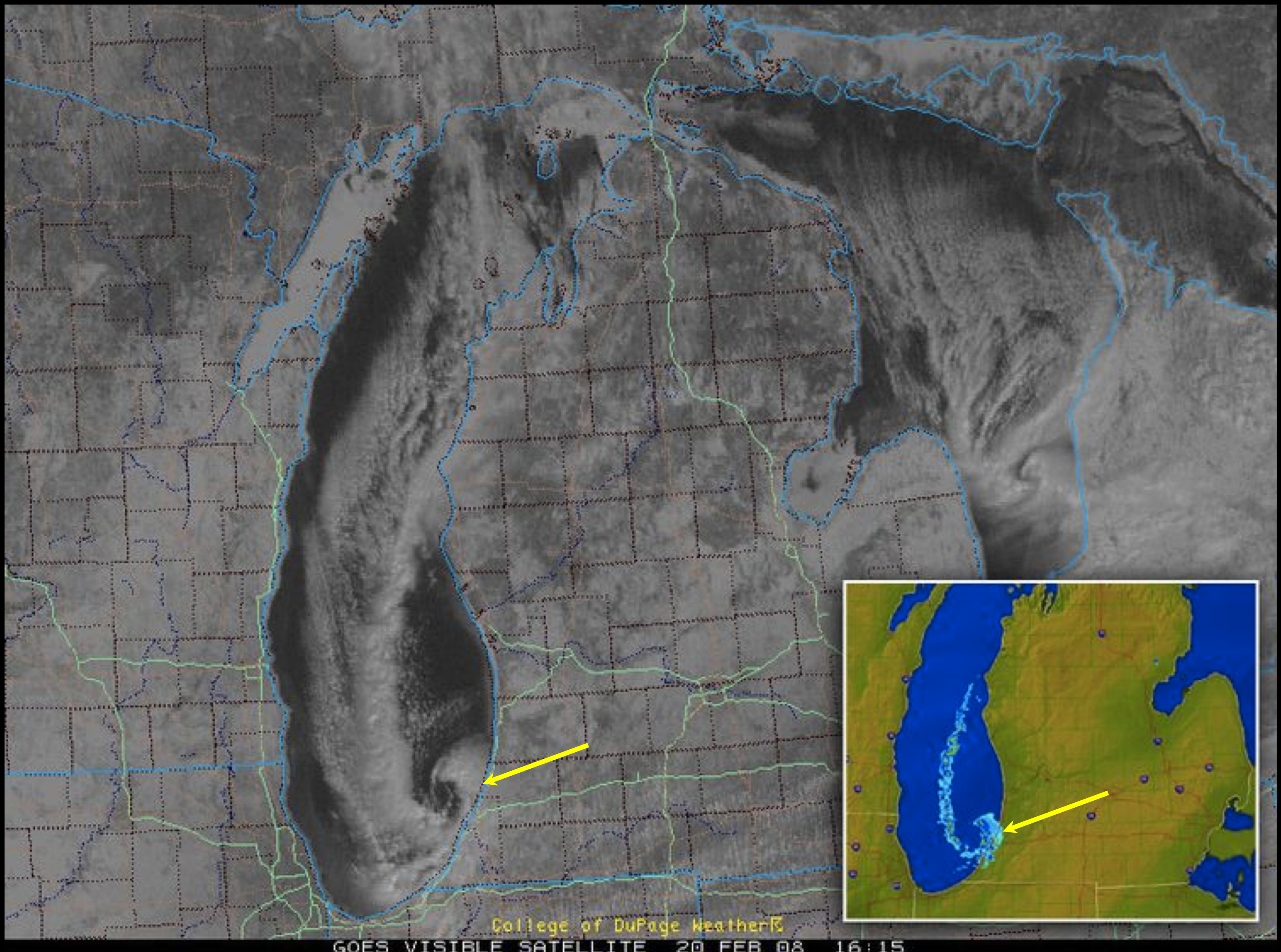
Japan Sea Polar Airmass Convergence Zone

Drivers include convergence in lee of Korean Highlands, coastal geometry, Sea of Japan SST distribution

Courtesy Tyler West

Other Terrain/Coastal Effects

Mesovortex



https://epod.usra.edu/blog/2008/06/lake-michigan-mesovortex-radar.html

Discussion

What controls the mode of lake- and sea-effect precipitation?


Lake Ontario and the
Tug Hill Plateau

Ontario Winter Lake-effect Systems (OWLeS)Field Campaign

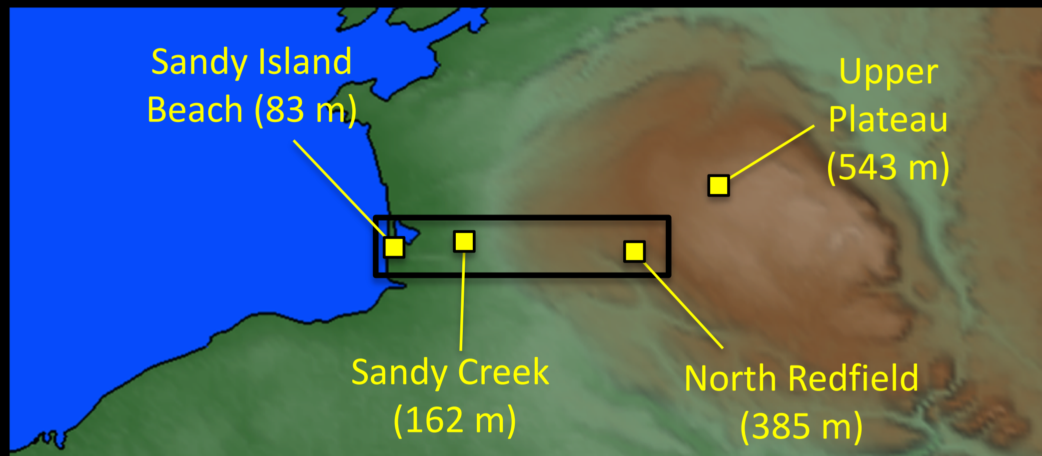
University of Wyoming King Air

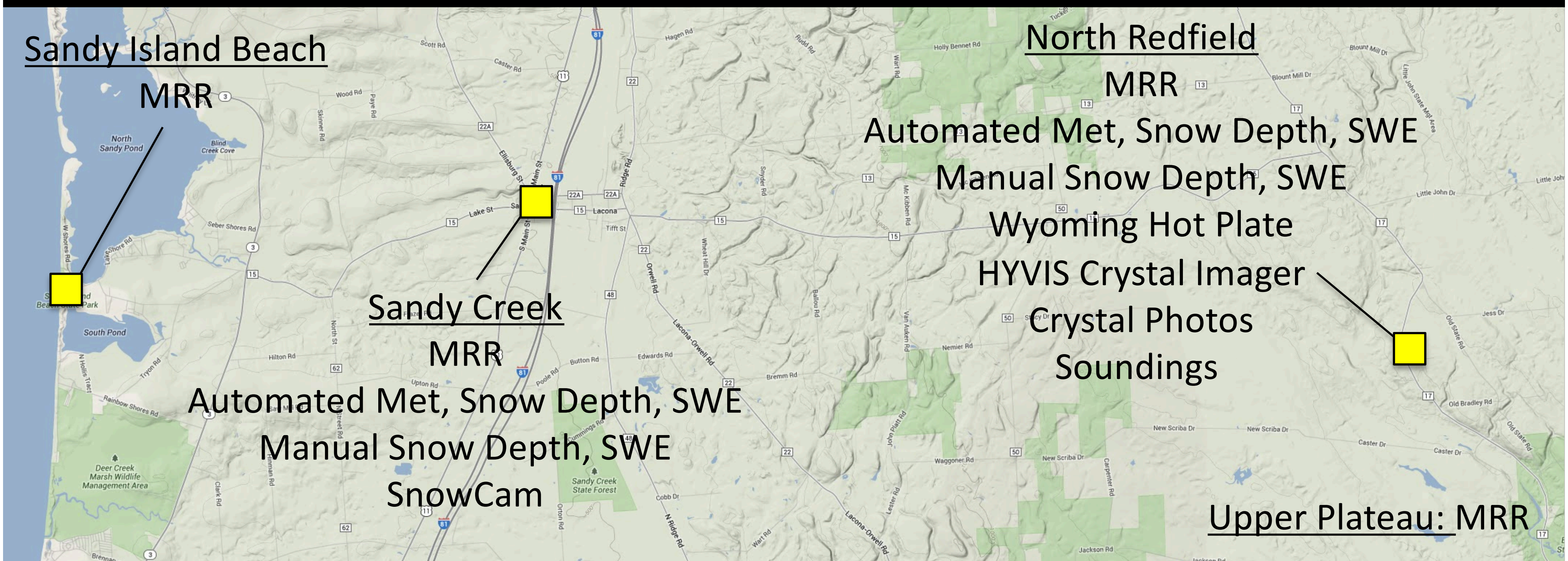
Three Doppler on Wheels (Photo: Karen Kosiba)


Five mobile sounding units

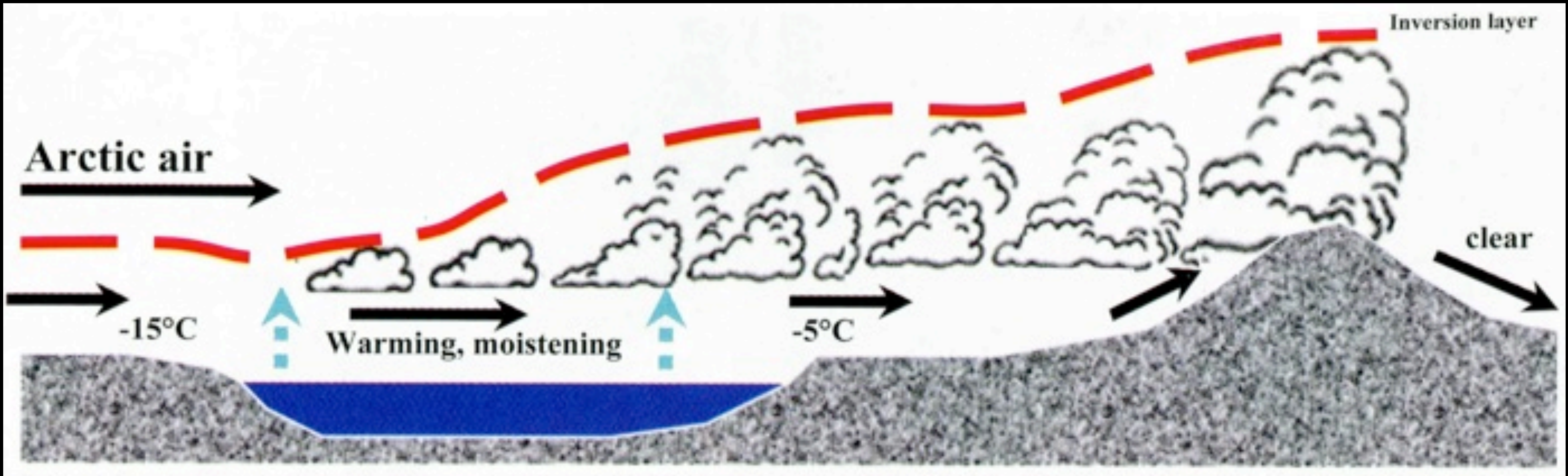
University of Alabama-Huntsville MIPS (Photo: Kevin Knupp, Ryan Wade)

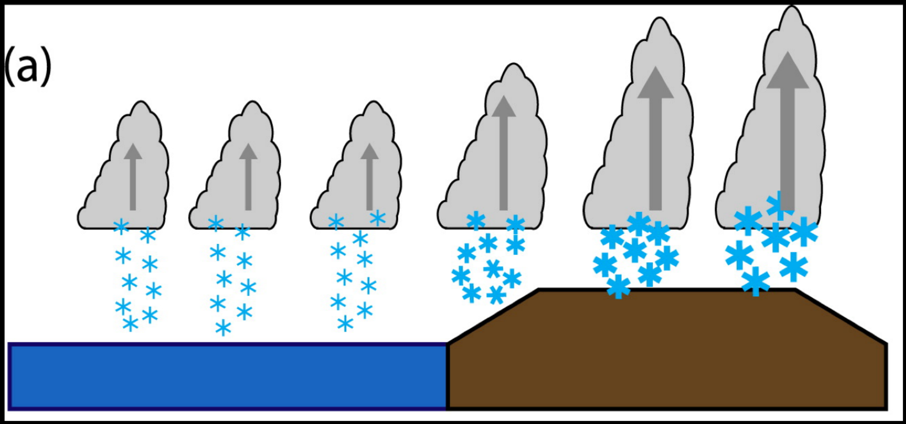
OWLeS Orographic Transect





Prior Conceptual Model

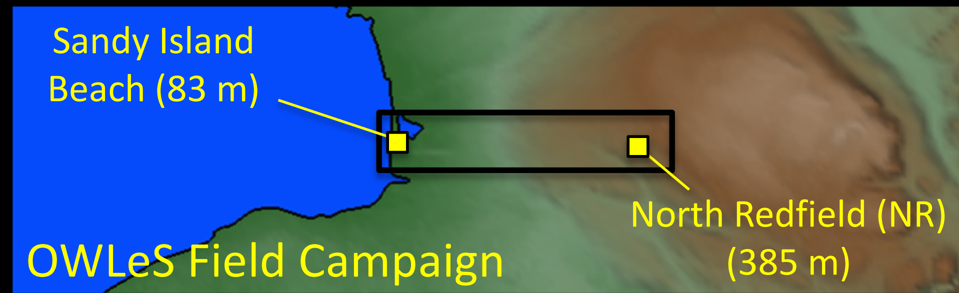


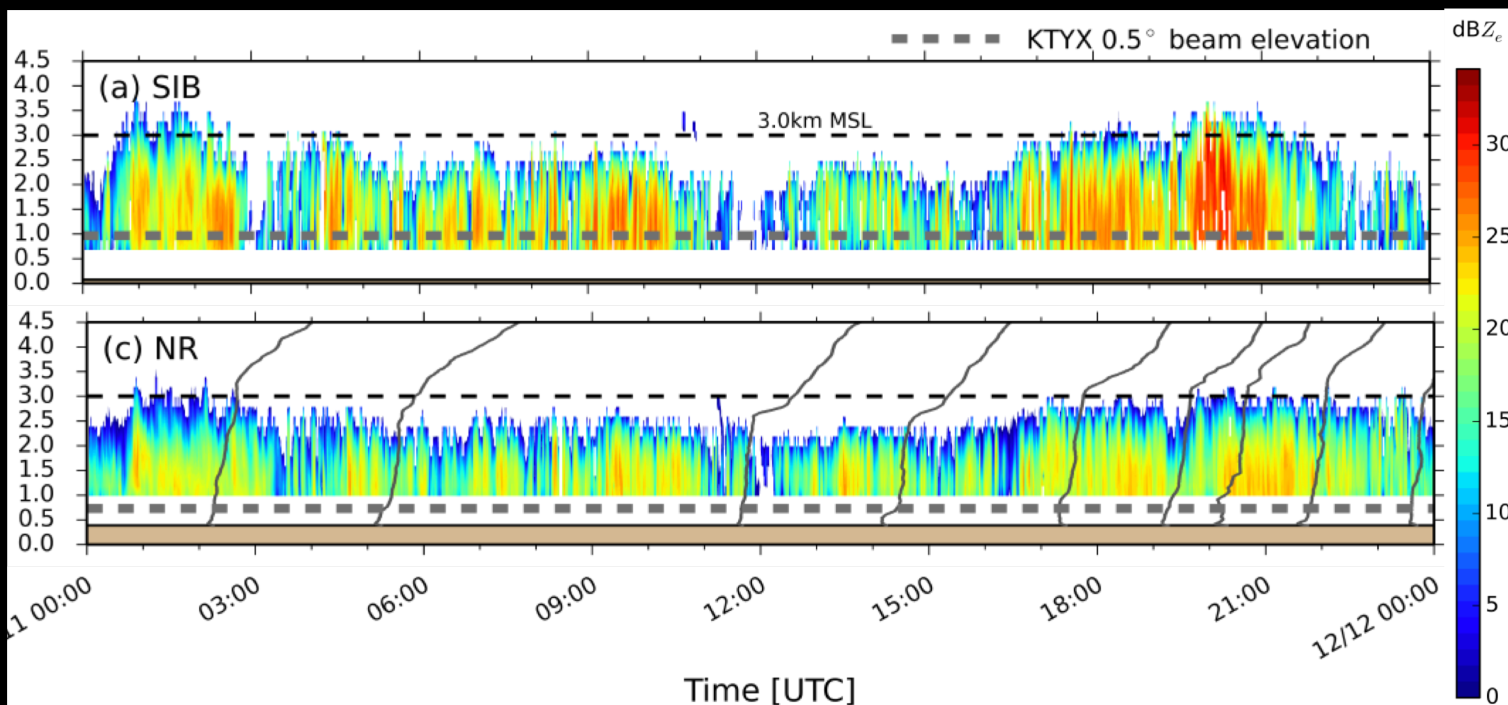


Orographic Invigoration of Convection

Lackmann (2011), Minder et al. (2015)

Tug Hill: Inland/Orographic Transition





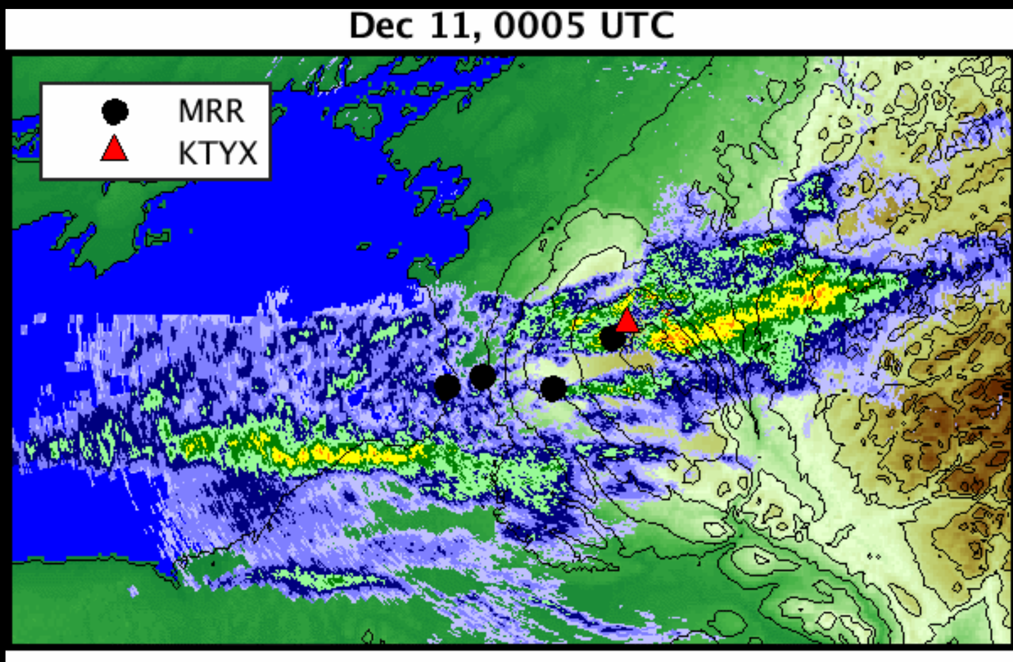
Instead: Convective to stratiform transition with snowfall

Becoming more continuous and persistent

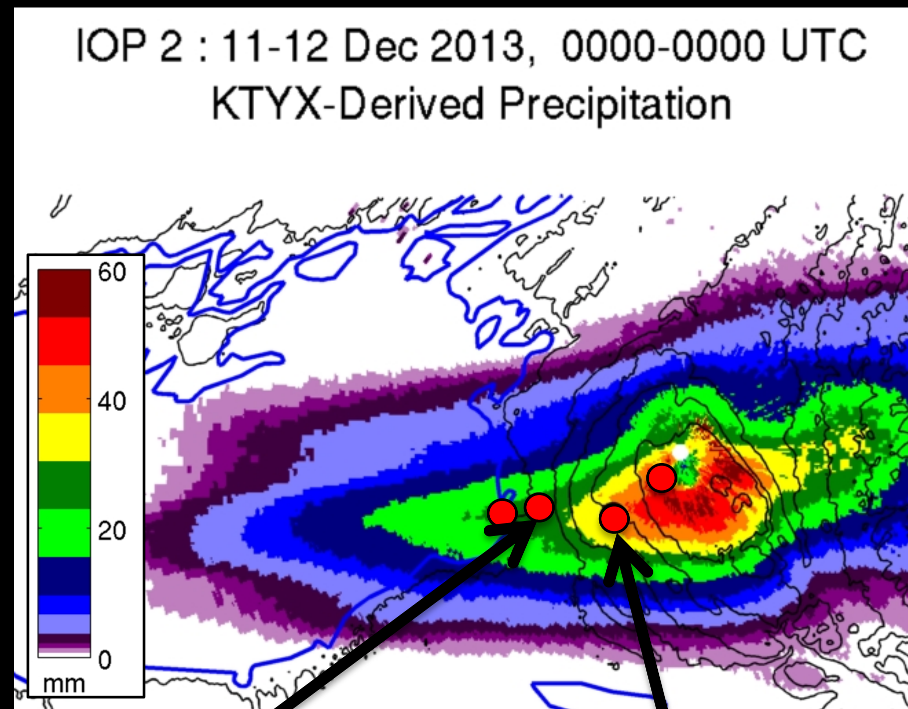
Minder et al. (2015)

Mesoscale & Orographic Forcing
OWLeS IOP2b

0000/11–0000/12 UTC Dec



Long-Lake Axis Parallel (LLAP) System



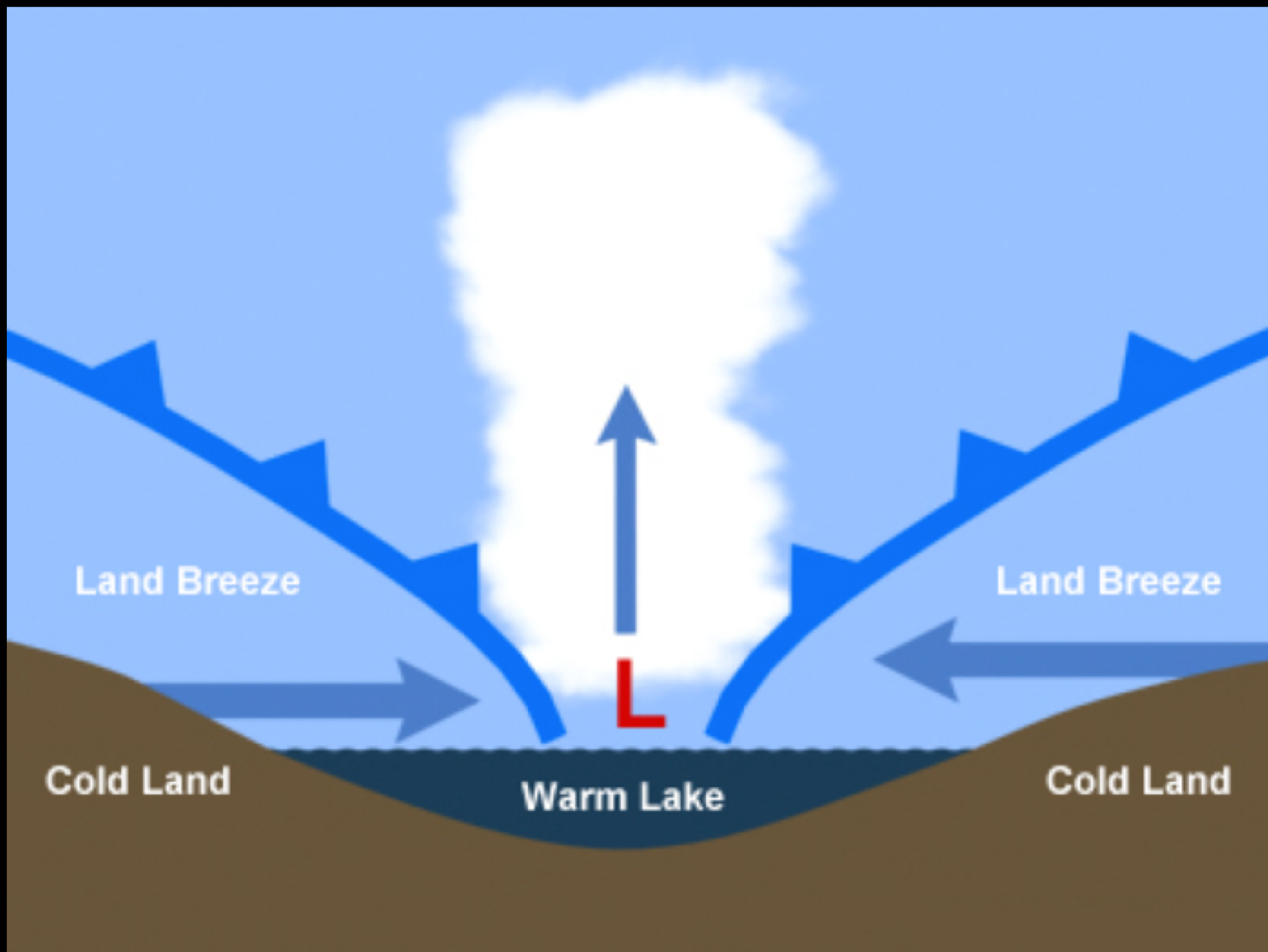
SC
Snow: 48 cm
LPE: 33.5 mm

NR
Snow: 102 cm
LPE: 62.5 mm

OR=NR/SC=1.9

Campbell et al. (2016)

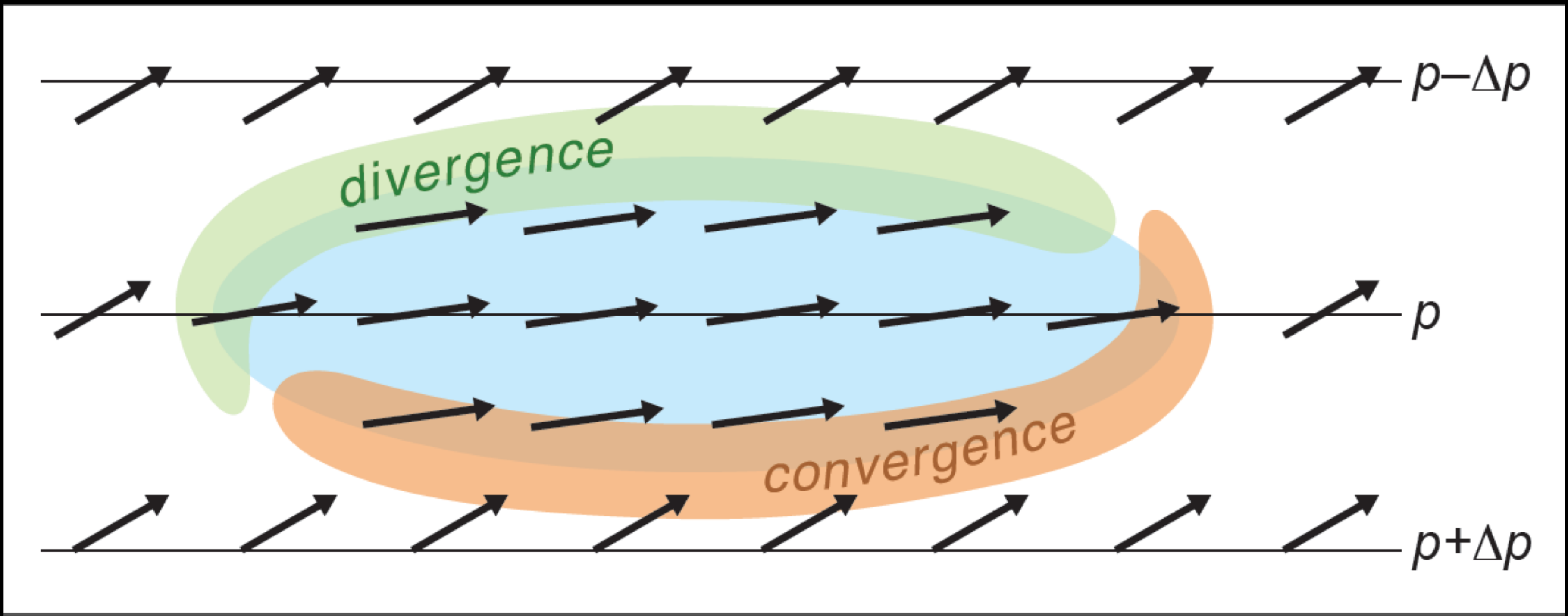
Forcing Conceptual Models



Thermally Forced Land Breeze Convergence
(Symmetric, Mid-Lake Axis)

UCAR/Comet

Forcing Conceptual Models



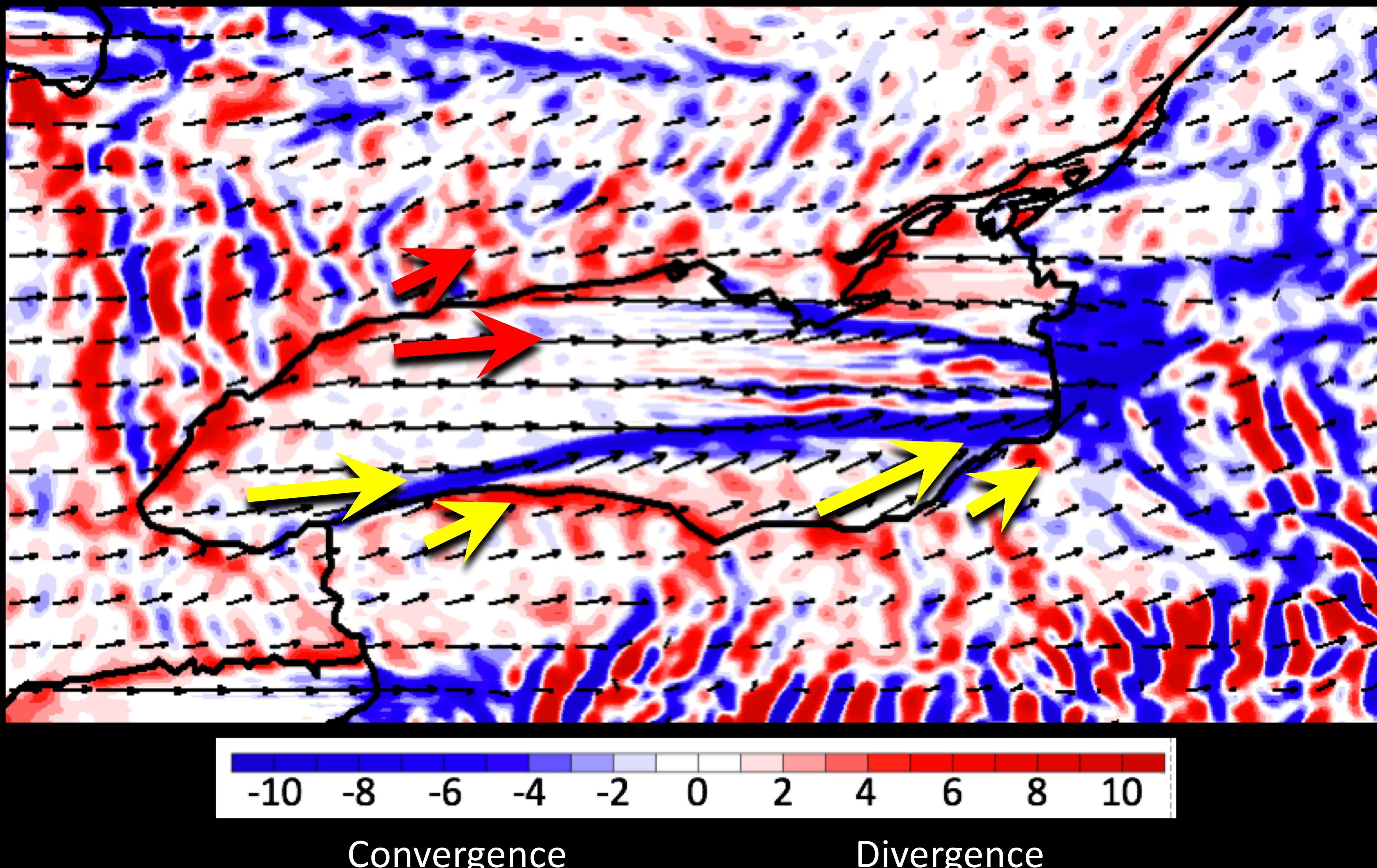
Frictionally Forced Land Breeze Convergence
(Streamwise-Right Shore)

Markowski and Richardson (2010)

Lake Ontario Not Symmetrical Or Oval!

Impact of Shoreline Geometry

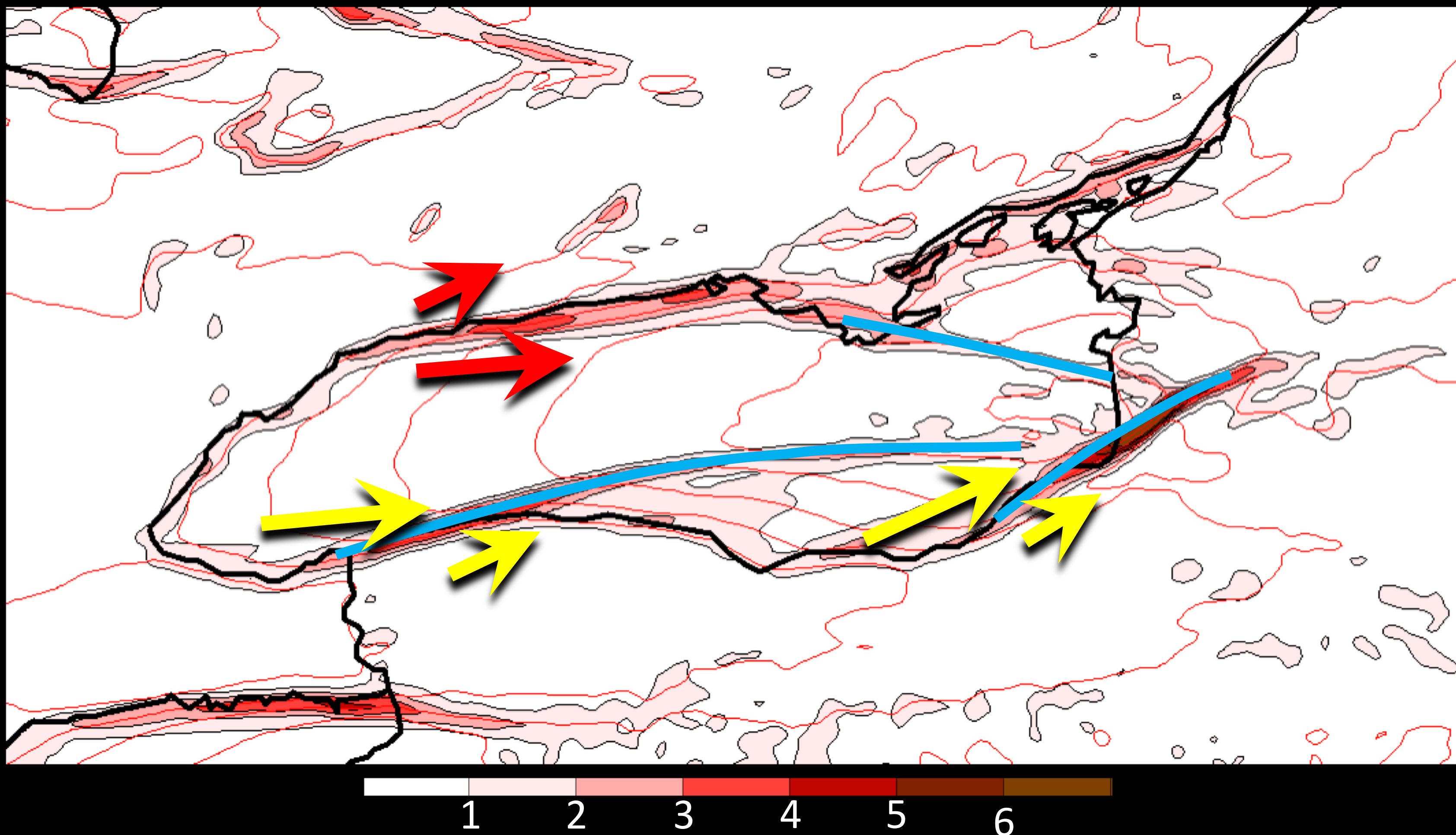
1200 UTC 11 Jan: WRF near-surface wind and divergence ($x10^{-4}$ s^{-1})



Steenburgh and Campbell (2017)

Impact of Shoreline Geometry

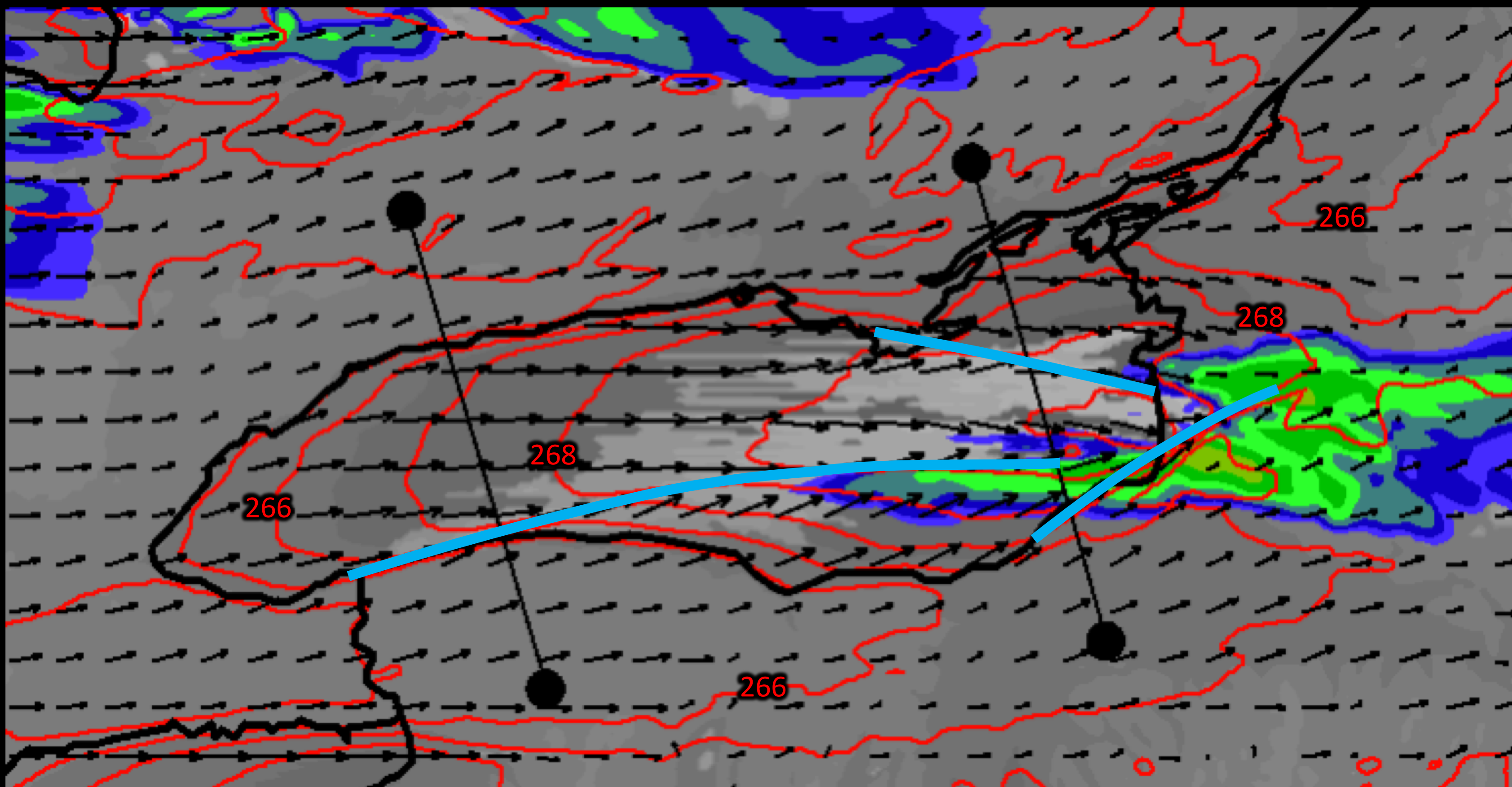
1200 UTC 11 Jan: WRF near-surface pot. temp. and pot. temp. gradient (K/10 km)



Steenburgh and Campbell (2017)

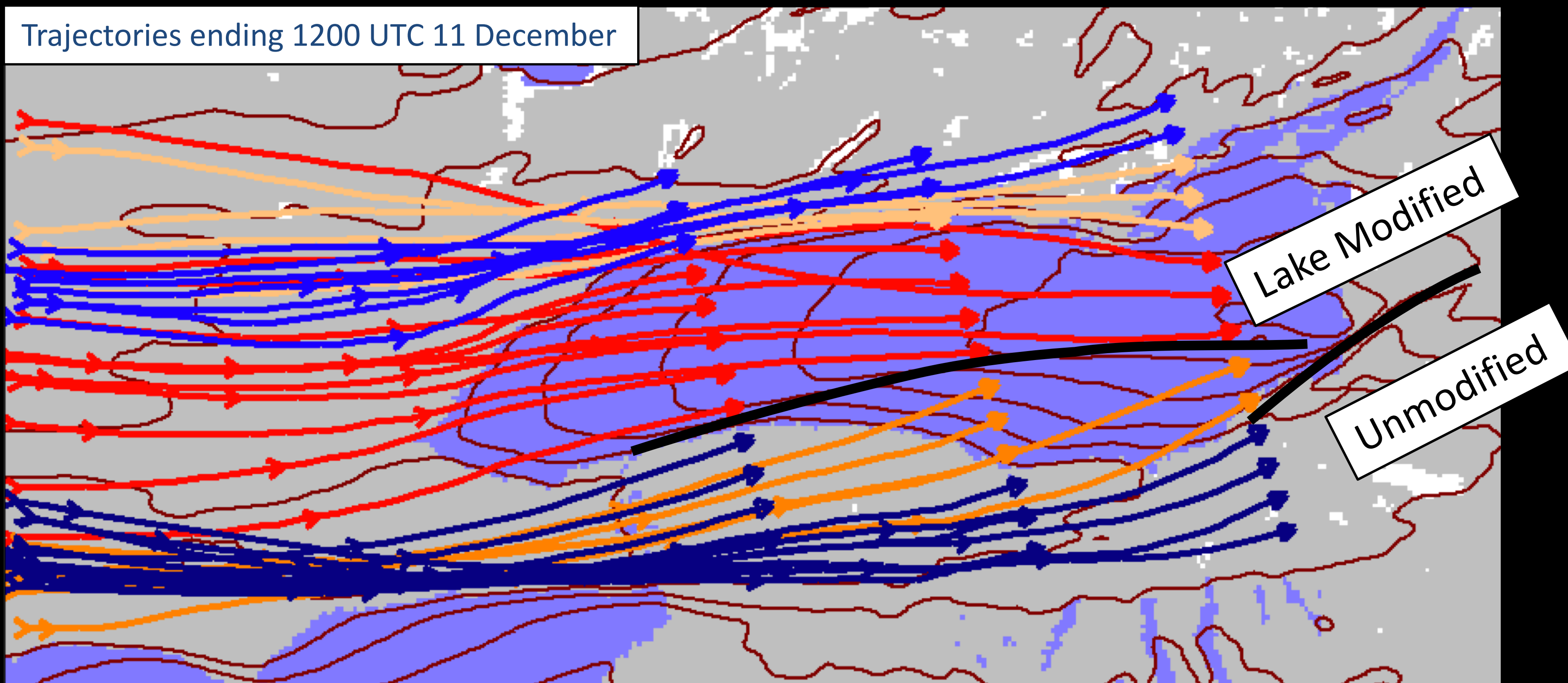
Impact of Shoreline Geometry

1200 UTC 11 Jan: WRF near-surface wind, IR, reflectivity, potential temperature



Steenburgh and Campbell (2017)

Impact of Shoreline Geometry



Cross west shore, long over-lake residence time

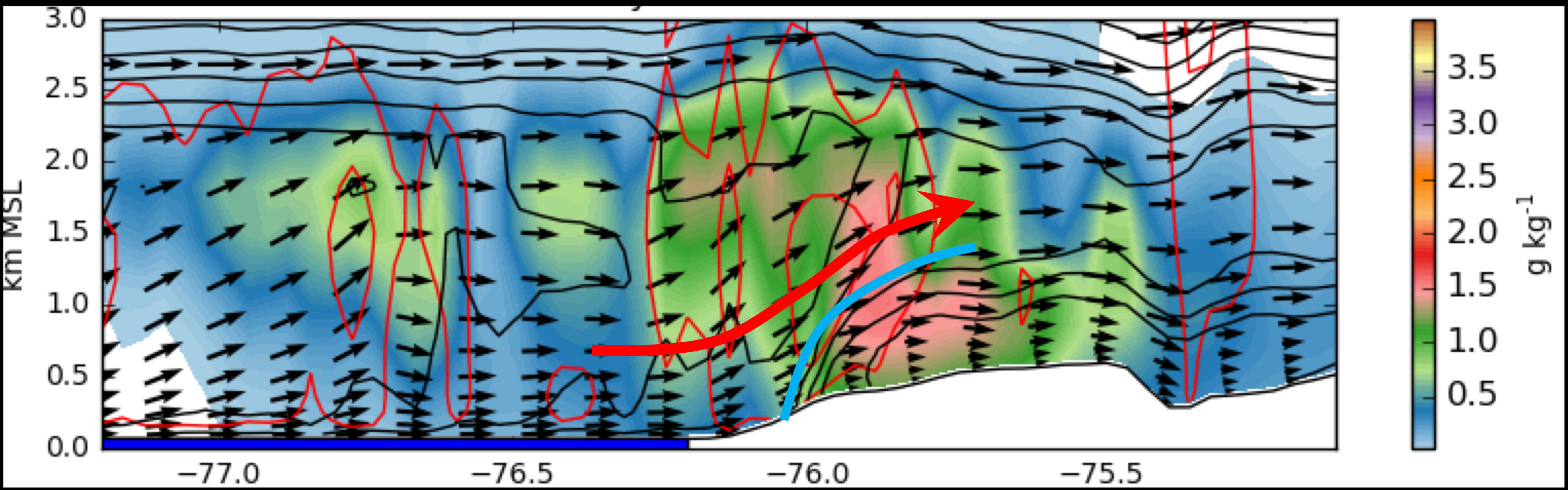
Cross north or south shore, short over-lake residence time

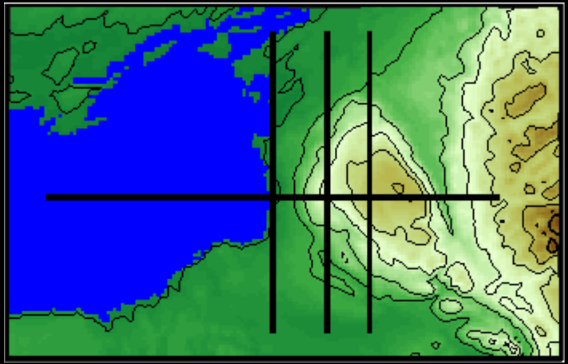
Confined to land, little or no lake modification

Steenburgh and Campbell (2017)

Getting Back to Tug Hill

1700 UTC 11 Jan: WRF theta-e (black contours), ascent (red contours), section-parallel circulation vectors, and hydrometeor mixing ratio (shaded)



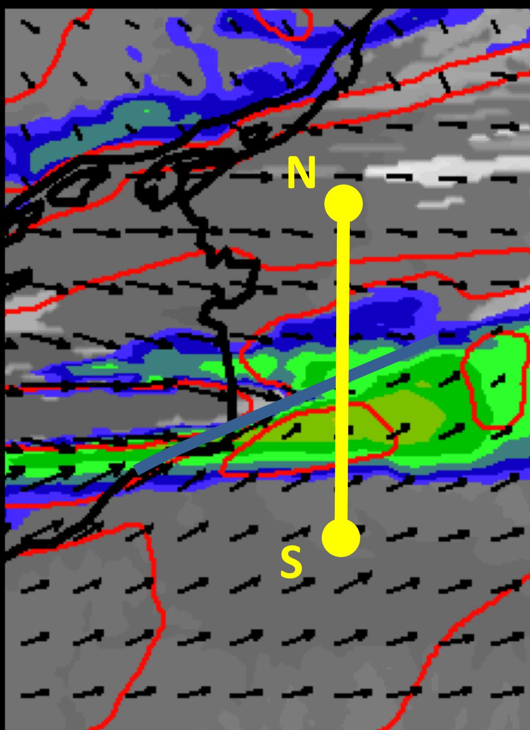


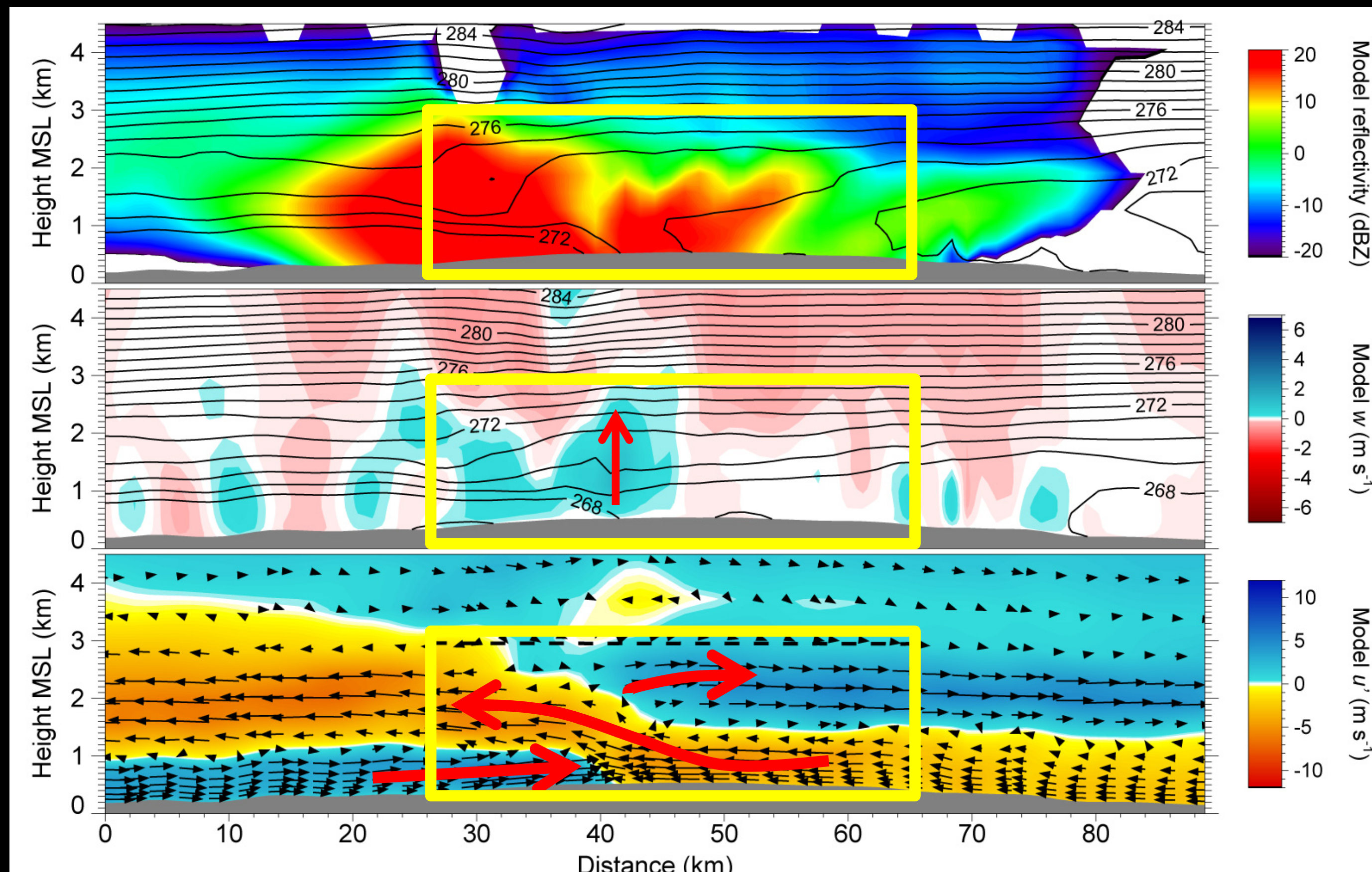
Zonal cross section across Tug Hill Plateau

Campbell and Steenburgh (2017)

Getting Back to Tug Hill

1930 UTC 11 December





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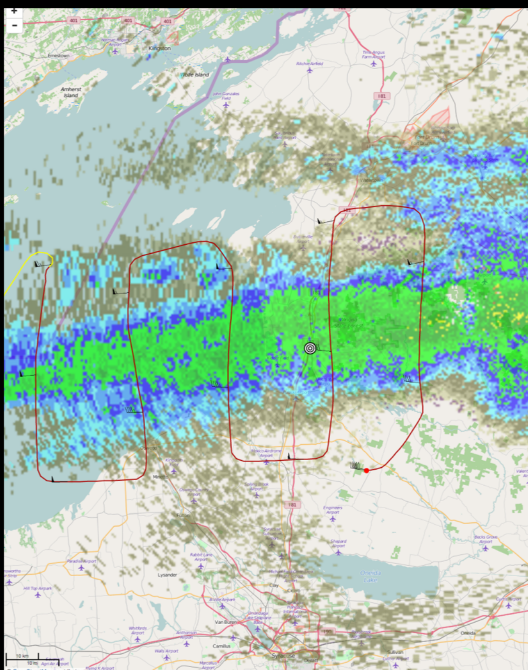
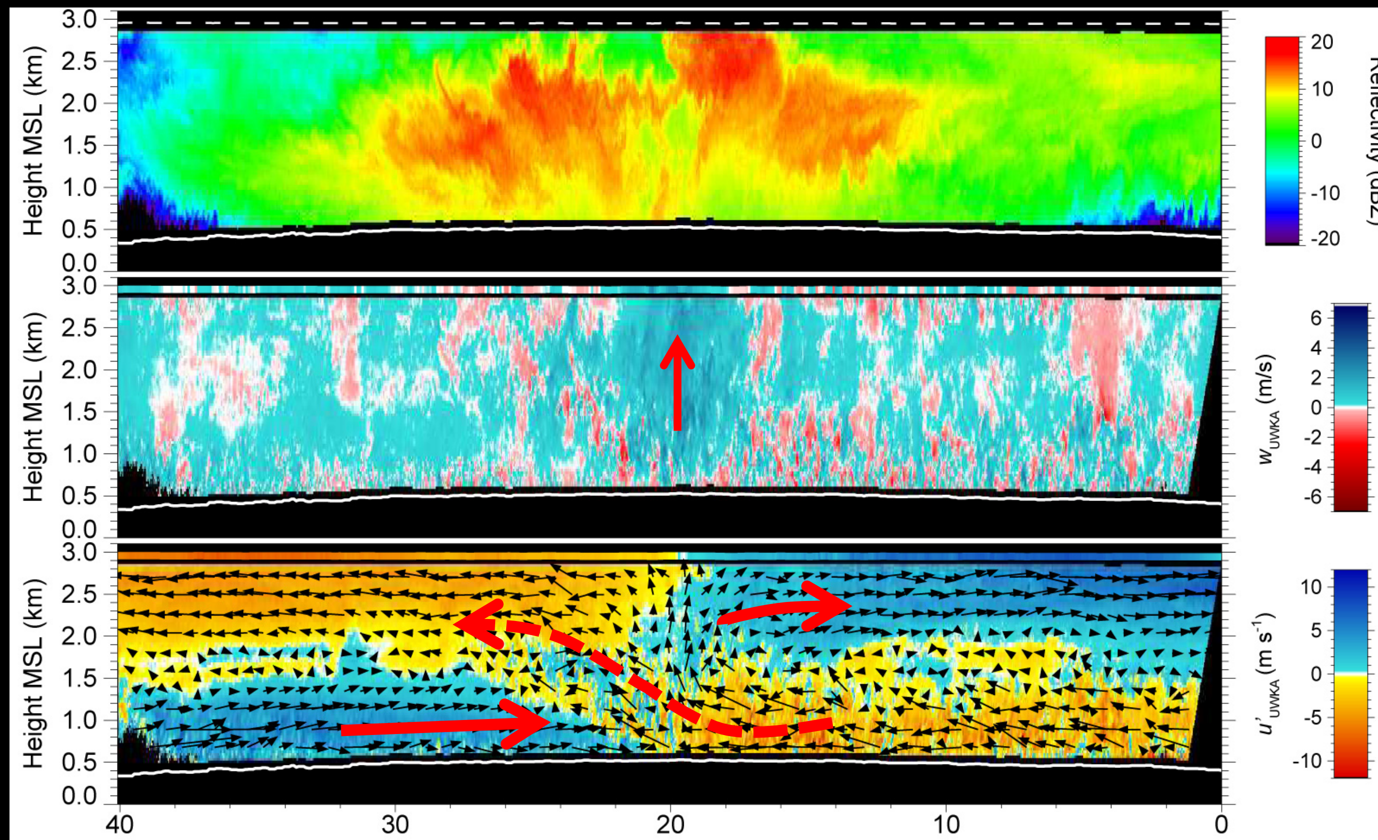
Bergmaier et al. (2017)

UWKA Cloud Radar

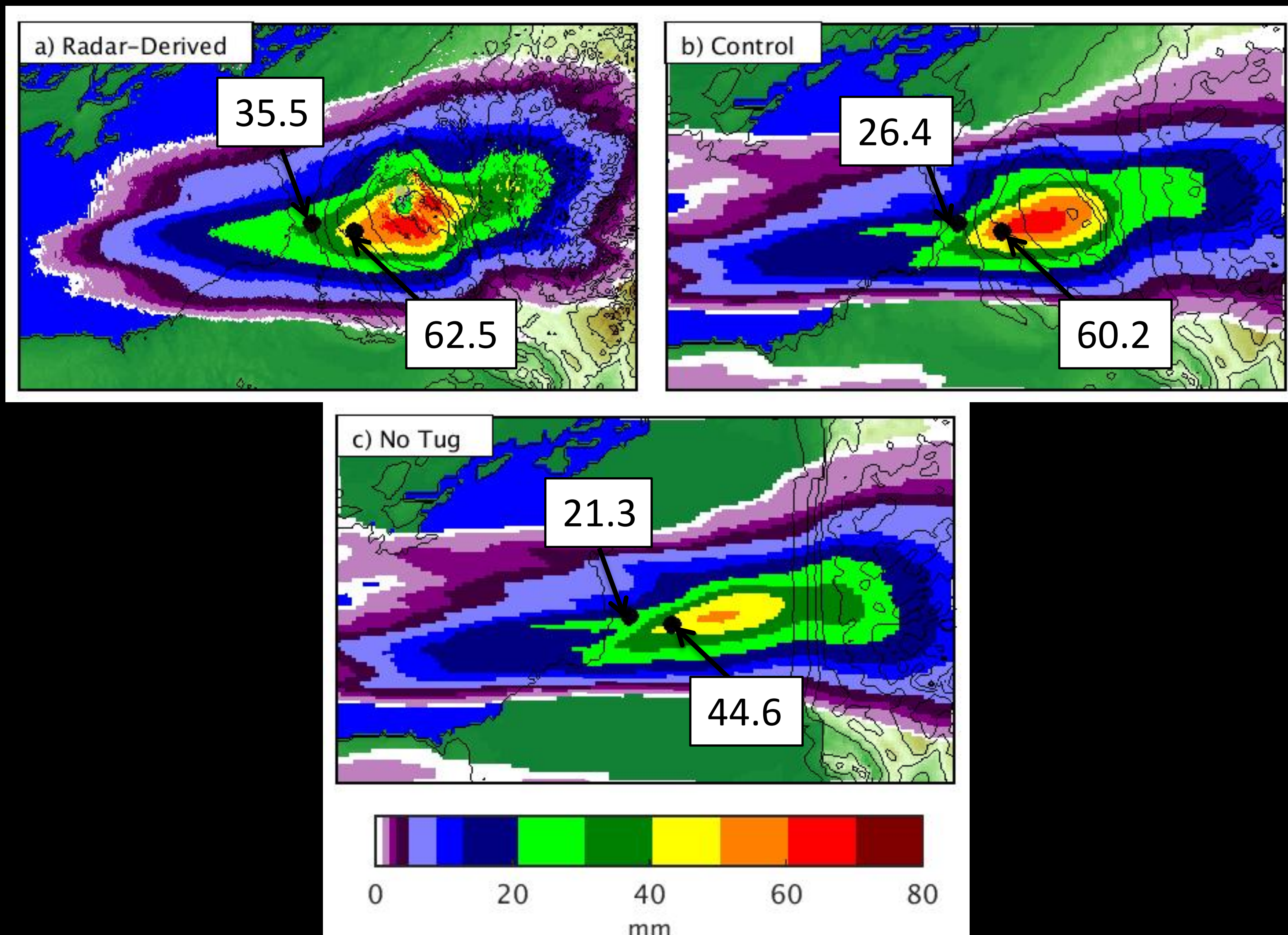


1928–1935 UTC 11 December



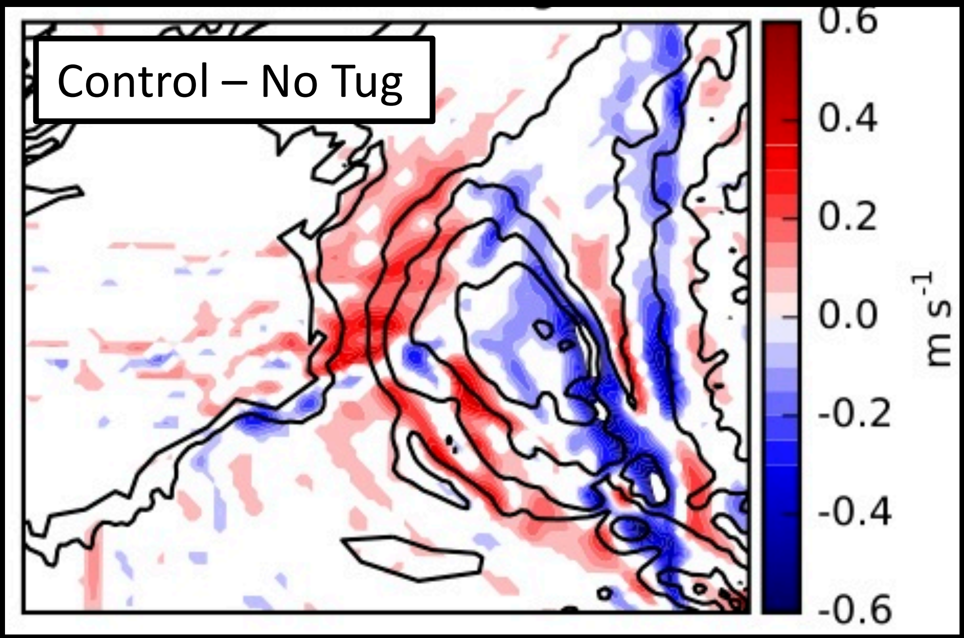
Bergmaier et al. (2017)

Model Terrain Sensitivity

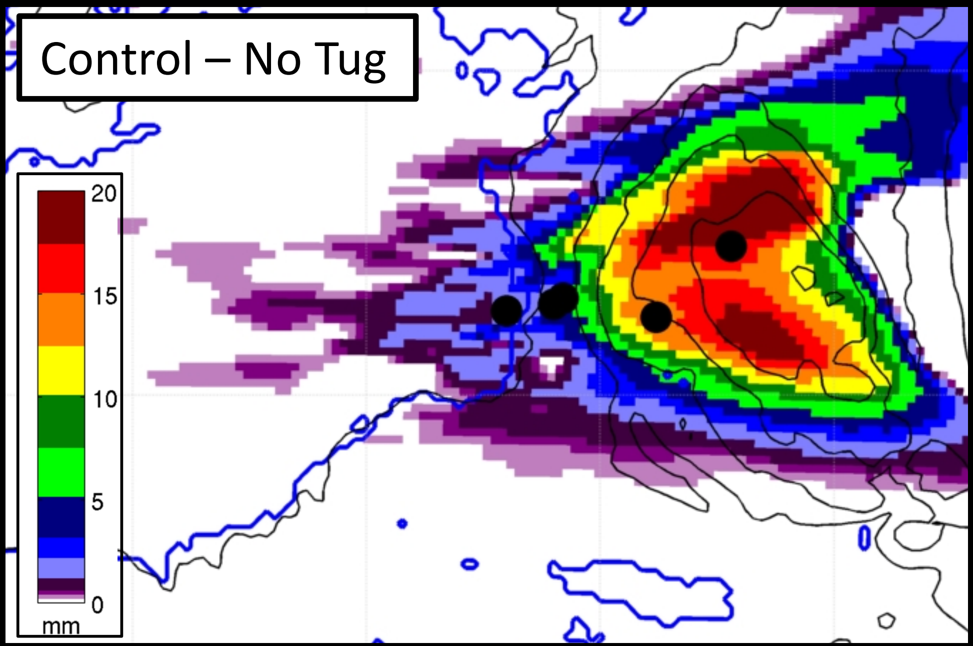


Campbell and Steenburgh (2017)

Tug Hill Influences



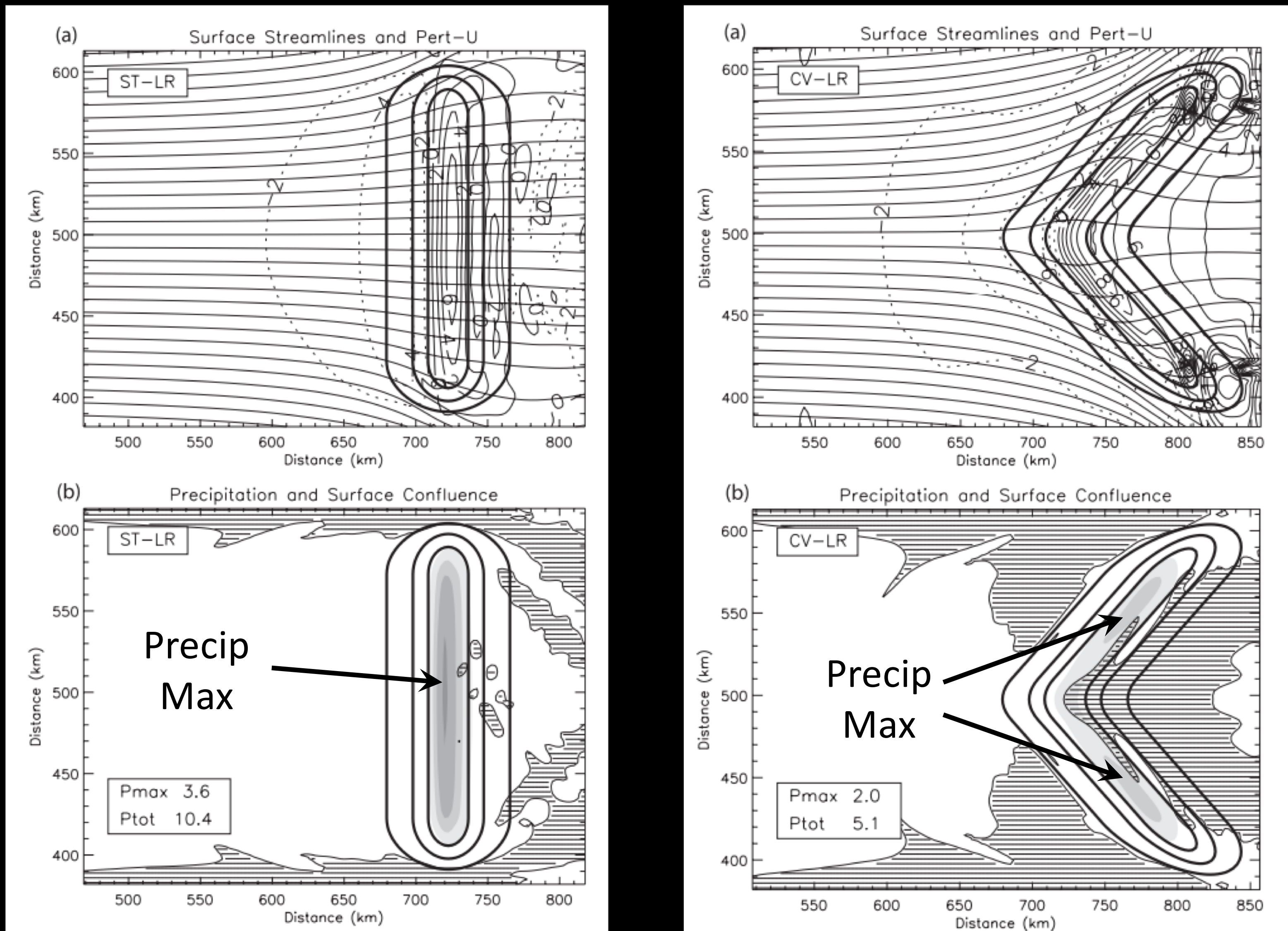
0300-2200 UTC
Vertical Velocity



0300-2200 UTC
Precipitation

Campbell and Steenburgh (2017)

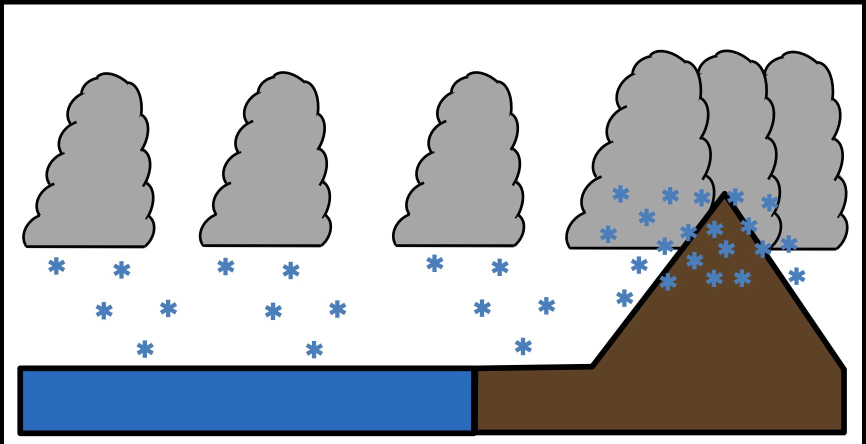
Tug Hill Influences



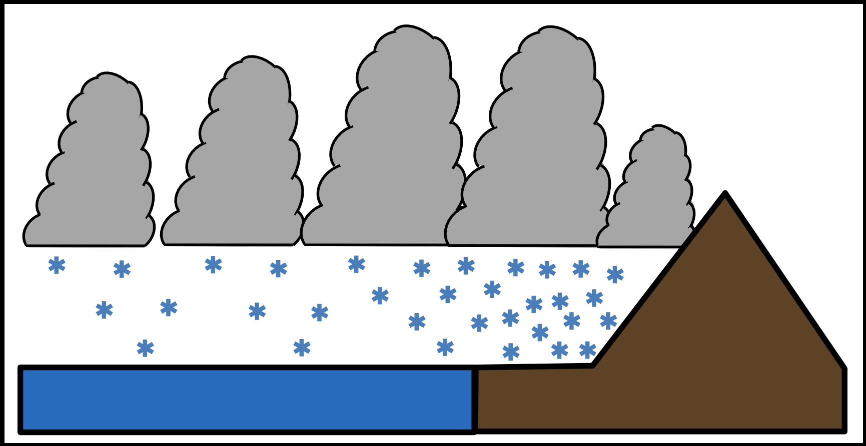
Watson and Lane (2012)


Japan’s Gosetsu Chitai

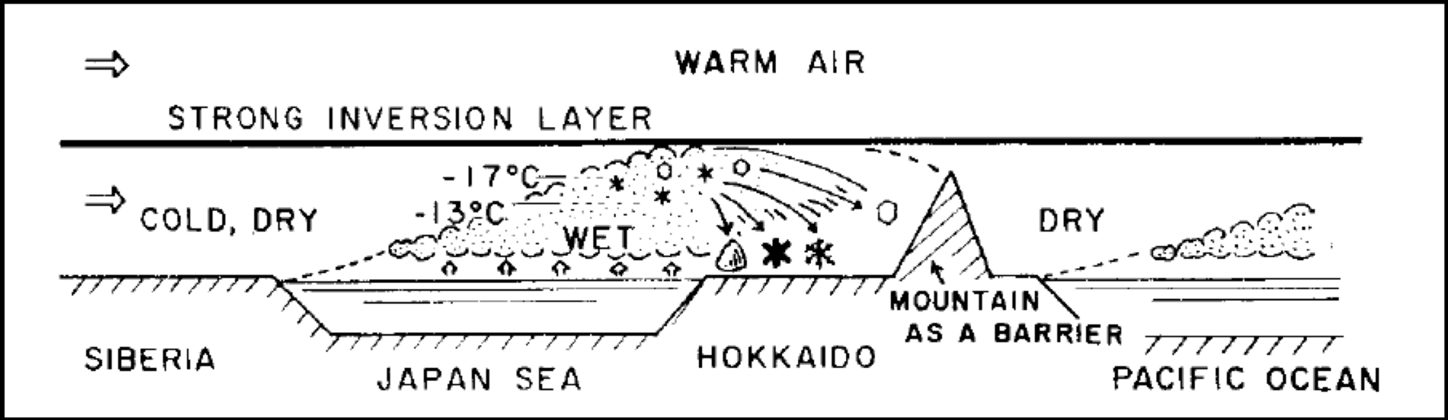
Yamayuki or Satoyuki?



Yamayuki
Mountain Snowfall



Satoyuki
Lowland Snowfall

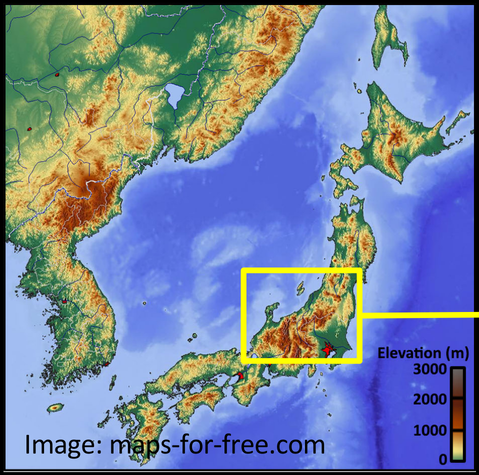


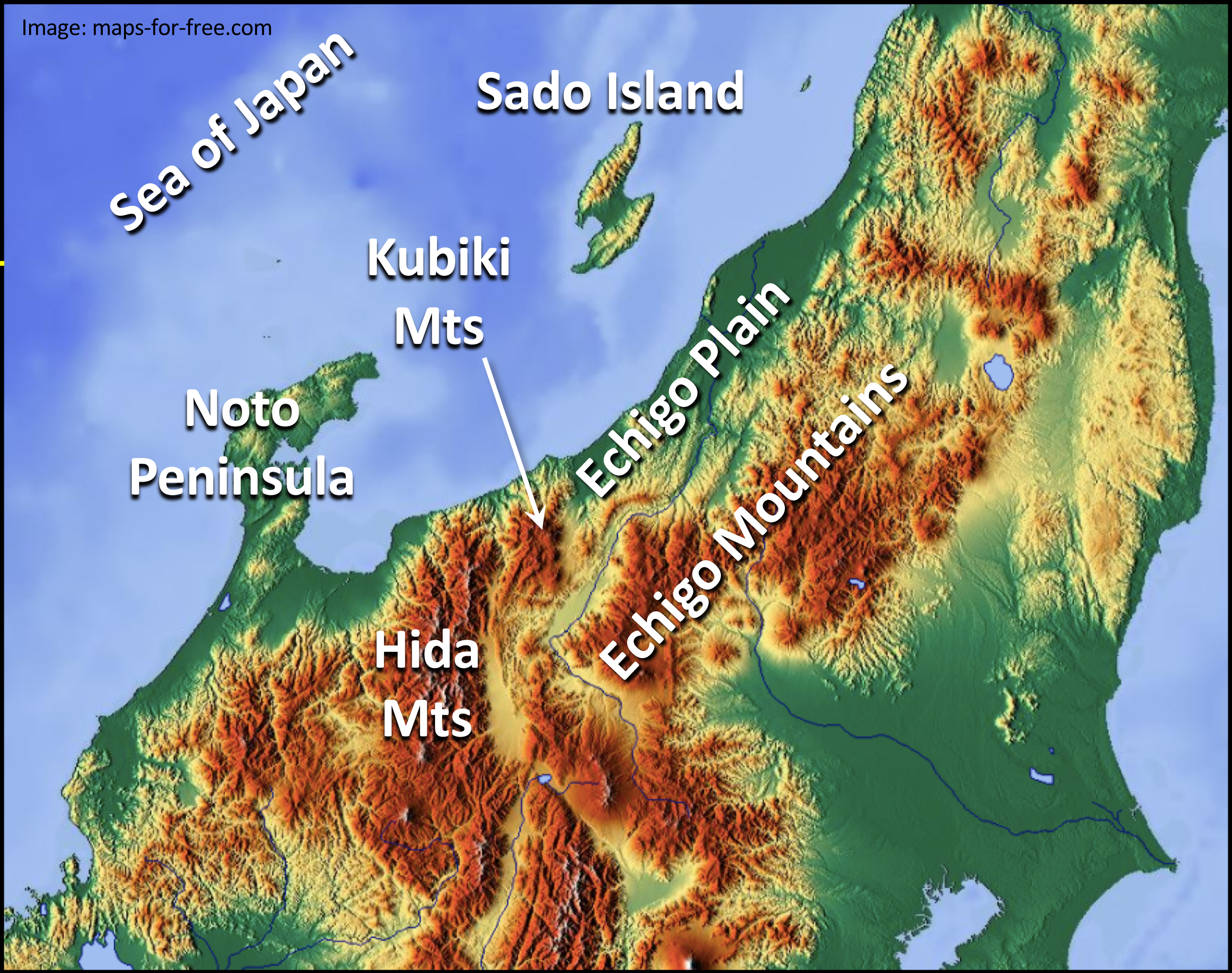
Conceptual Model of Satoyuki Snowfall
Magono et al. (1966)

Discussion

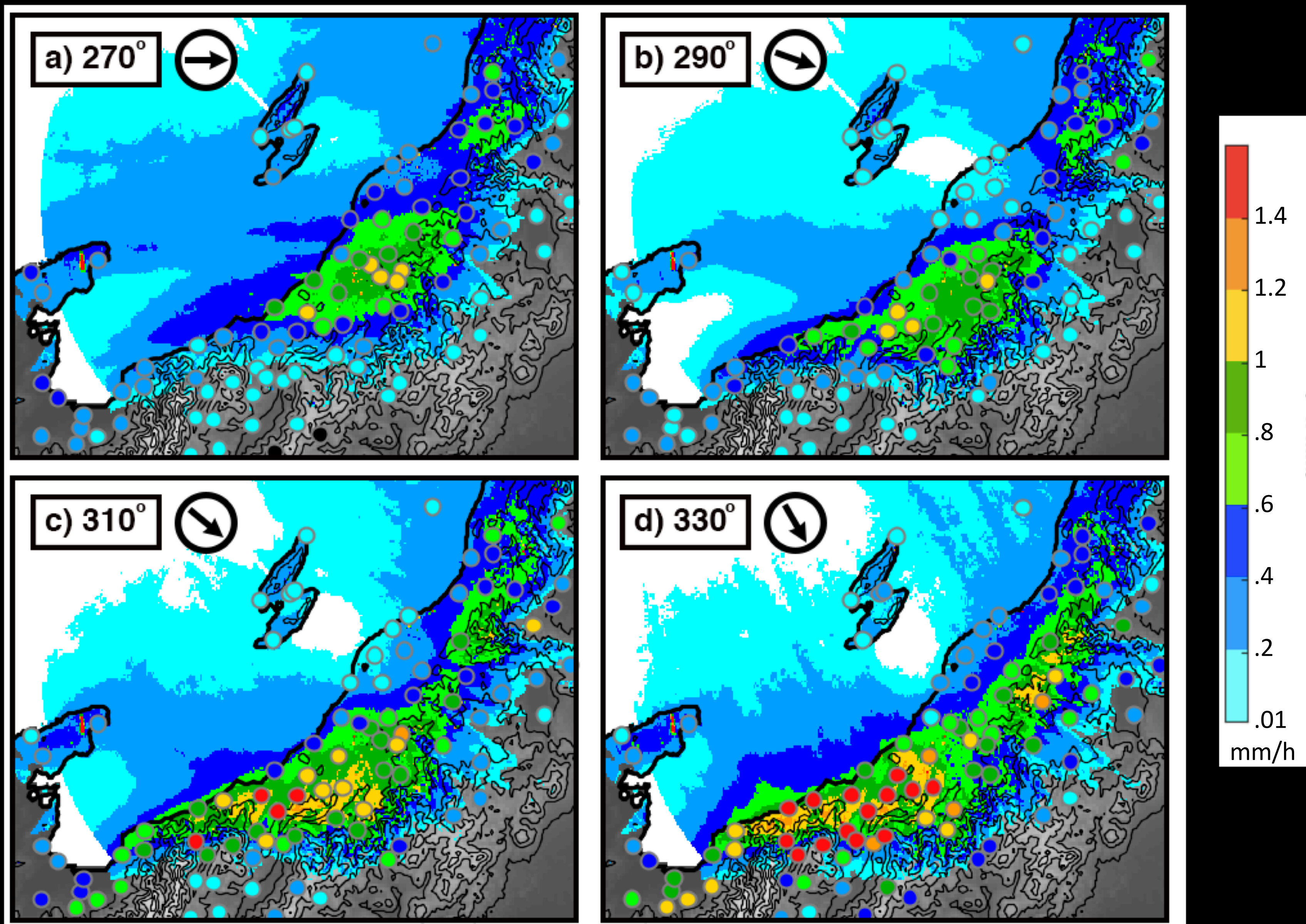
What controls whether a storm is Yamayuki or Satoyuki?

Hokuriku Region



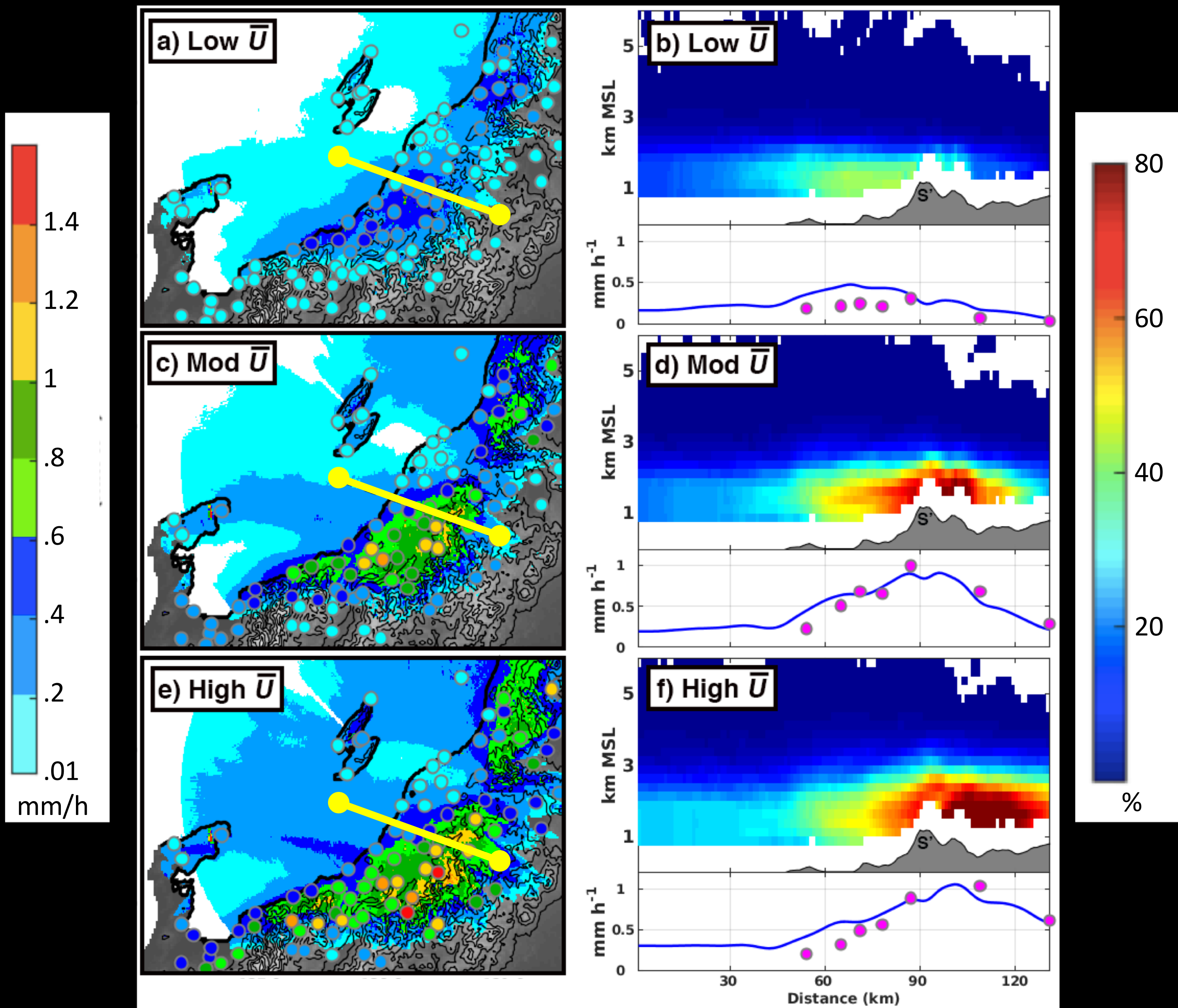


Wind direction (Moderate *U*)



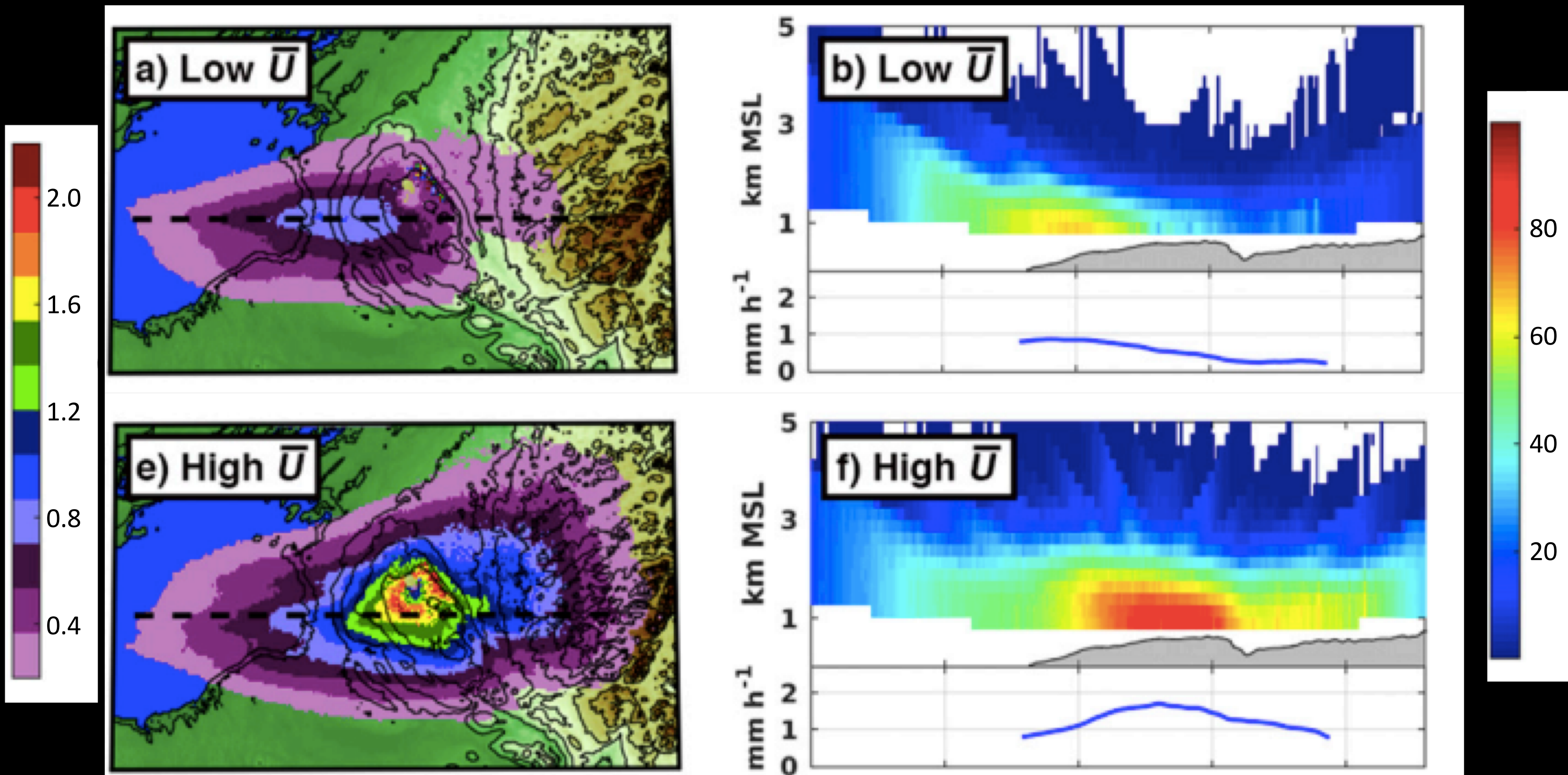
Veals et al. (2019)

Wind Speed (290˚)



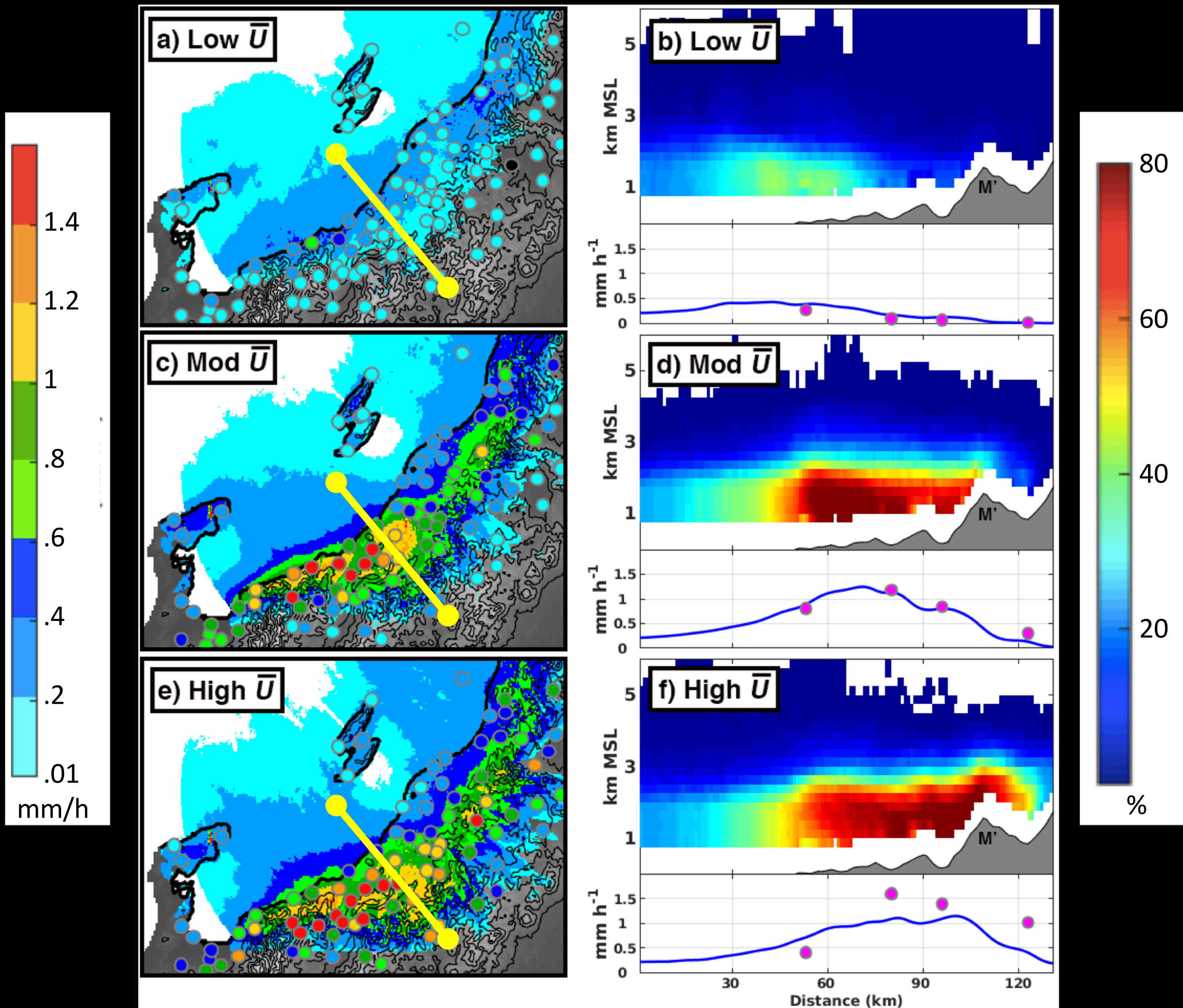
Veals et al. (2019)

Tug Hill Comparison



Veals et al. (2018)

Wind Speed (320˚)



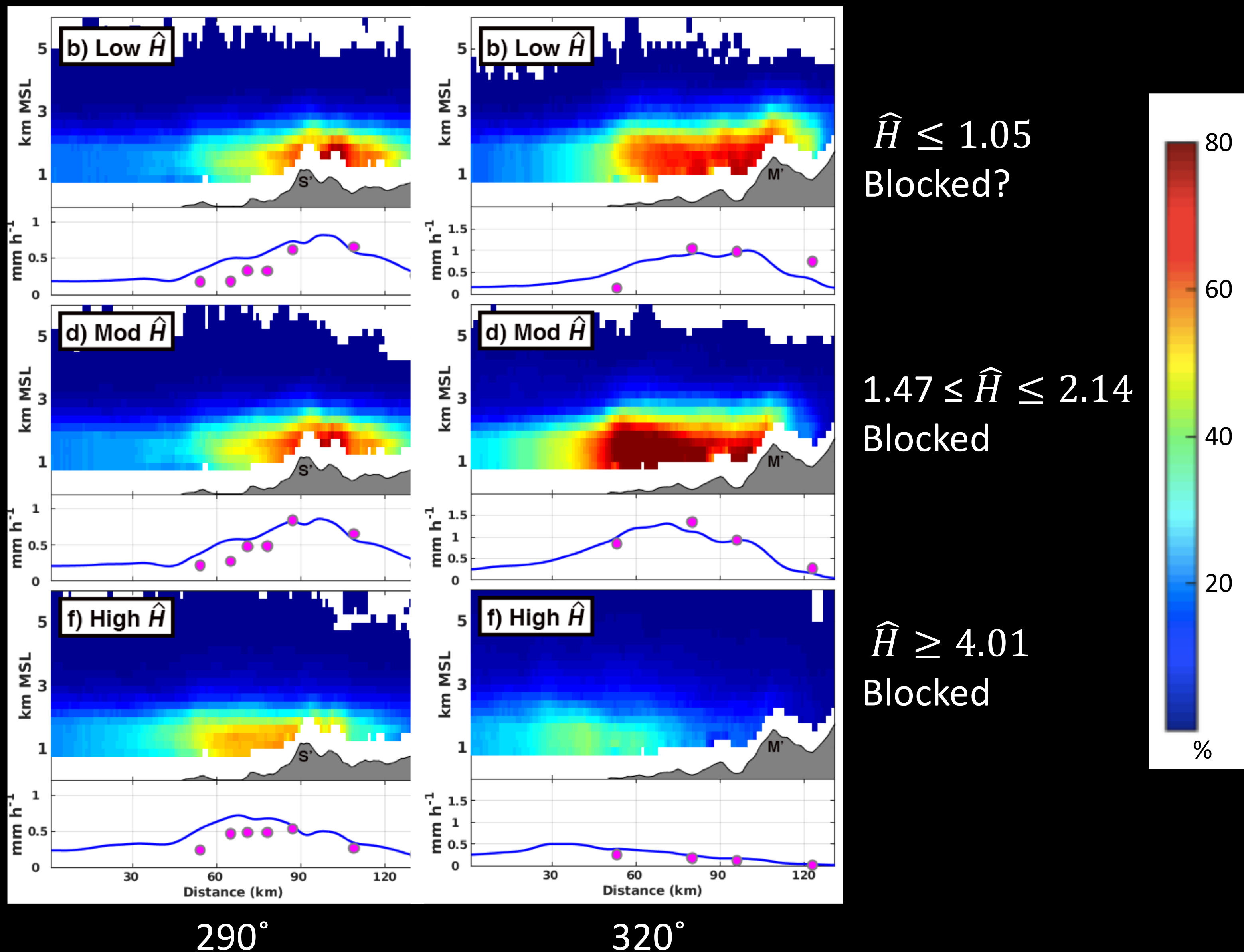
Veals et al. (2019)

Non-Dimensional Mountain Height

$\hat{H} \leq 0.46$
Unblocked

$0.59 \leq \hat{H} \leq 0.75$
Unblocked

$\hat{H} \geq 1.03$
Blocked?



$\hat{H} \leq 1.05$
Blocked?

$1.47 \leq \hat{H} \leq 2.14$
Blocked

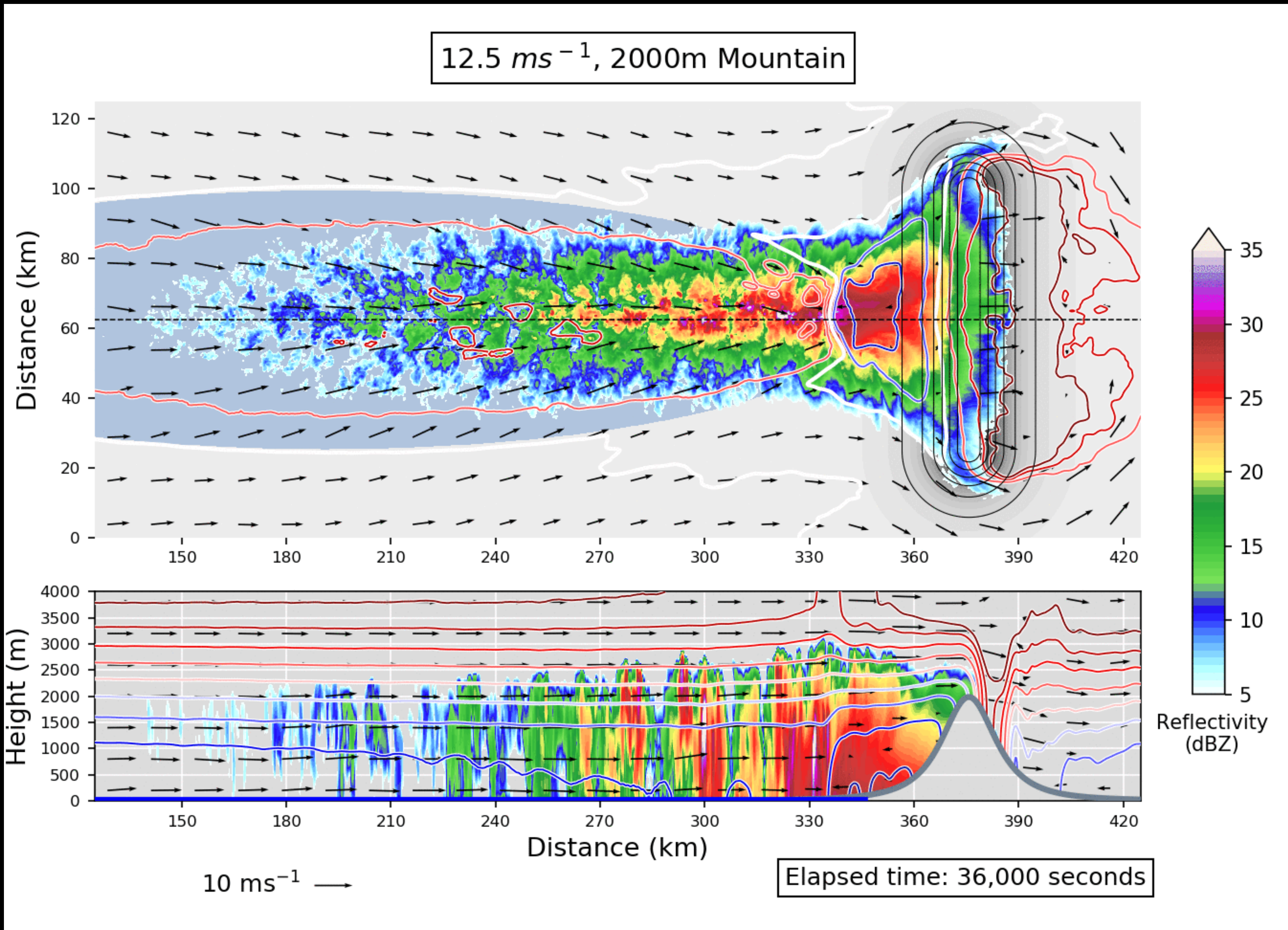
$\hat{H} \geq 4.01$
Blocked

Veals et al. (2019)

Cloud Modeling

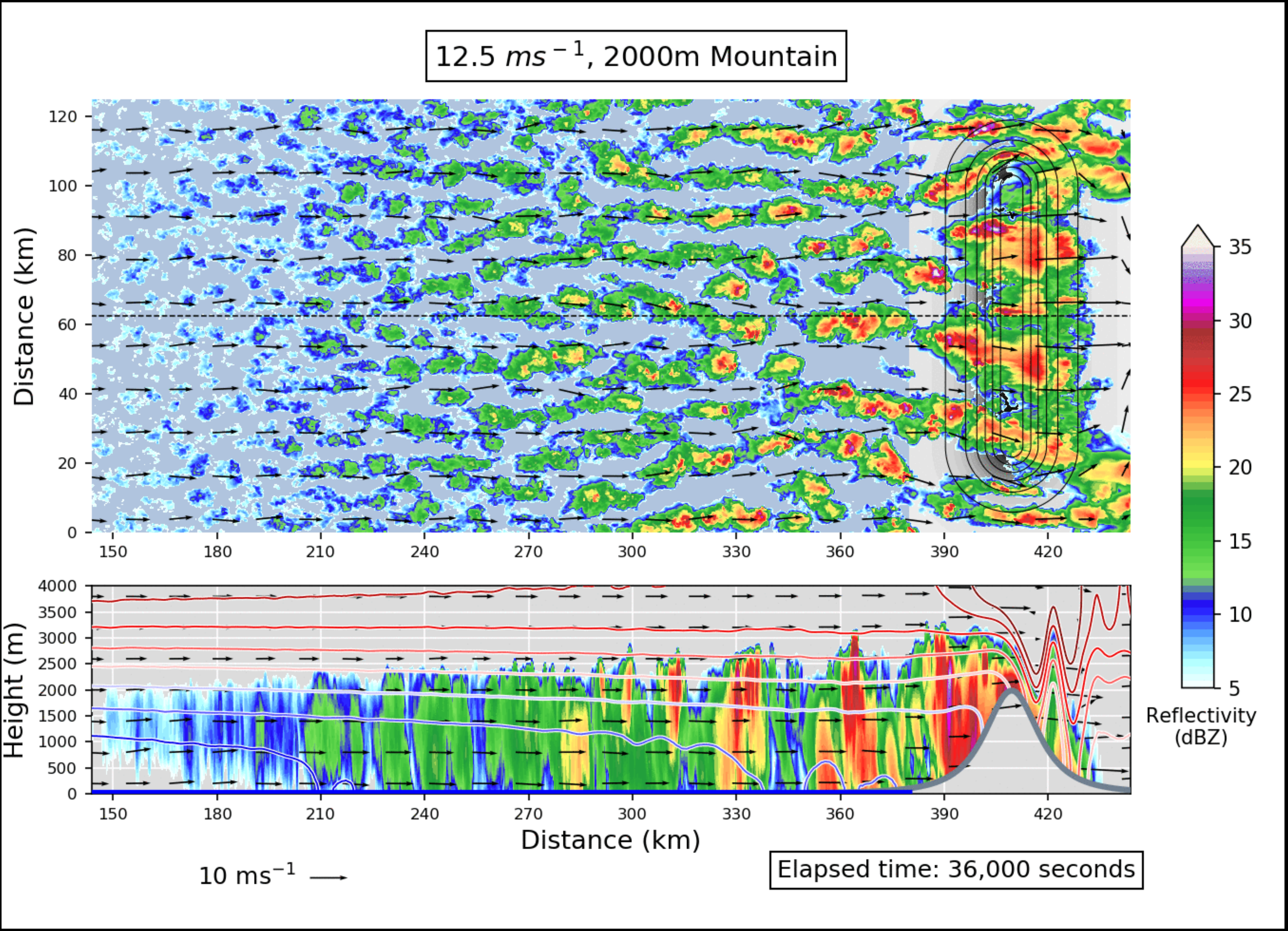
Photo: J. Brian A. Morganti, stormeffects.com

Oval Lake LLAP Band



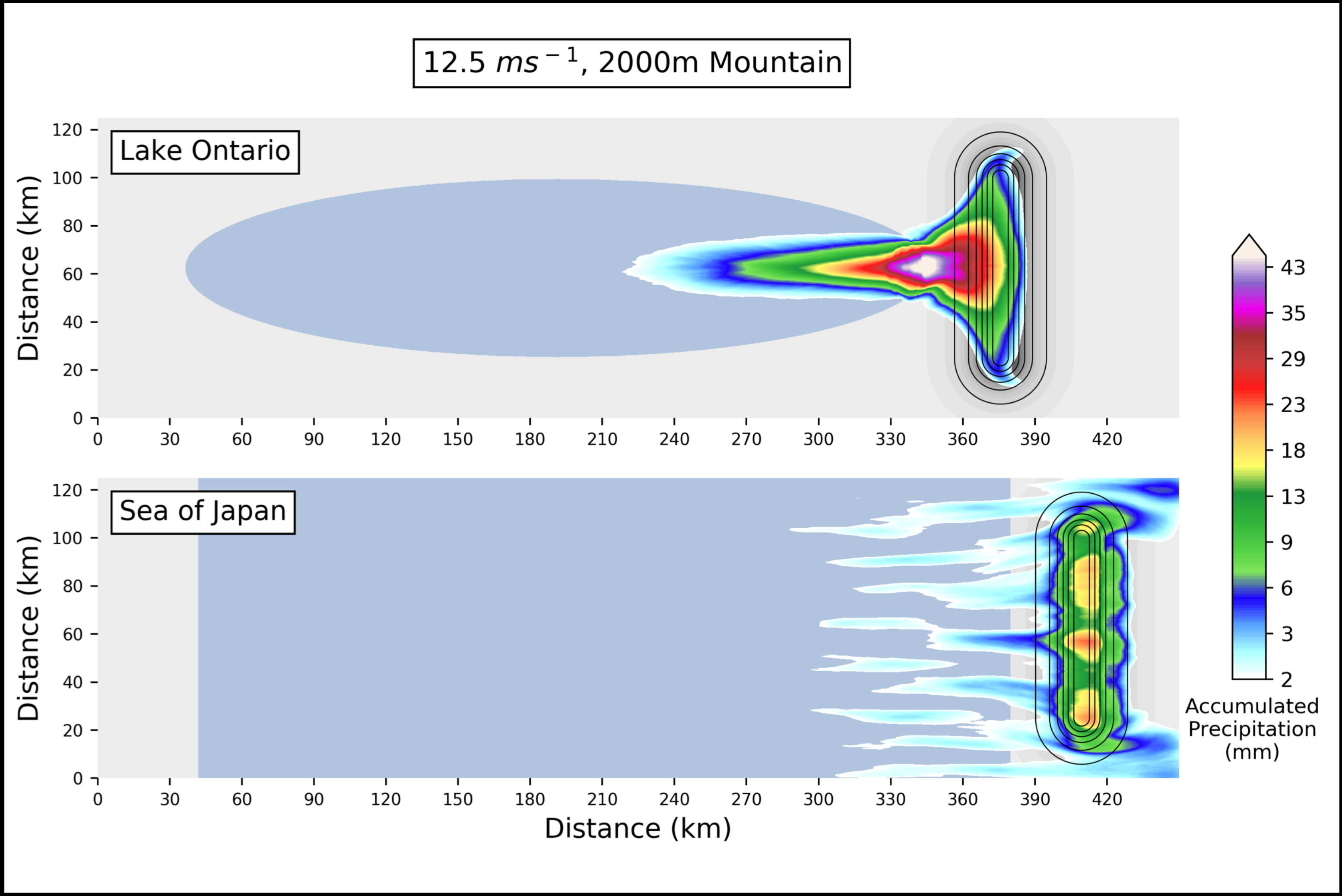
Courtesy Tom Gowan

Broad Lake Open Cellular



Courtesy Tom Gowan

Oval vs. Wide/LLAP vs. Open Cell



Discussion: With same upstream sounding and terrain, why is the orographic ratio different in these two cases?

Courtesy Tom Gowan

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 are multifaceted and affect the initiation, intensity, and morphology of lake-effect systems

References

Alcott, T. I., W. J. Steenburgh, and N. F. Laird, 2012: Great Salt Lake-effect precipitation: Observed frequency, characteristics, and environmental factors. *Wea. Forecasting*, **27**, 954-971.

Asai, T., 1972: Thermal instability of a shear flow turning the direction with height. *J. Meteor. Soc. Japan*, **50**, 525–532

Bergmaier, P.T. and B. Geerts, 2016: Airborne radar observations of lake-effect snowbands over the New York Finger Lakes. *Mon. Wea. Rev*., **144**, 3895–3914.

Bergmaier, P. T., B. Geerts, L. S. Campbell, and W. J. Steenburgh, 2017: The OWLeS IOP2b lake-effect snowstorm: Dynamics of the secondary circulation. *Mon. Wea. Rev*., **145**, 2437-2459.

Burt, C. C., 2007: *Extreme Weather: A Guide and Record Book*. W. W. Norton Company, 320 pp.

Campbell, L. S., and W. J. Steenburgh, 2017: The OWLeS IOP2b lake-effect snowstorm: Mechanisms contributing to the Tug Hill Precipitation Maximum. *Mon. Wea. Rev*., **145**, 2461-2478.

Campbell, L. S., W. J. Steenburgh, P. G. Veals, T. W. Letcher, and J. R. Minder, 2016: Lake-effect mode and precipitation enhancement over the Tug Hill Plateau during OWLeS IOP2b. *Mon. Wea. Rev*., 144, 1729–1748.

Campbell, L. S., W. J. Steenburgh, Y. Yamada, M. Kawashima, and Y. Fujiyoshi, 2018: Influences of orography and coastal geometry on a transverse-mode sea-effect snowstorm over Hokkaido Island, Japan. *Mon. Wea. Rev*., **146**, 2201–2220.

Hjelmfelt, M. R., 1990: Numerical study of the influence of environmental conditions on lake-effect snowstorms over Lake Michigan. *Mon. Wea. Rev.*, **118,** 138-150.

Lackmann, G., 2011: *Midlatitude Synoptic Meteorology*. Amer. Meteor. Soc., 360 pp.

Leffler, R. J., R. M. Downs, G. W. Goodge, N. J. Doesken, K. L. Eggleston, and D. Robinson, 1997: Evaluation of the reported January 11–12, 1997, Montague, New York, 77-inch, 24-hour lake-effect snowfall. National Weather Service Special Rep., 60 pp. [Available online at http://www1.ncdc.noaa.gov/pub/data/cmb/extremes/ncec/mantague-ny-snowfall-24hour.pdf.]

References

Magono, C., K. K. Kikuchi, T. Kimura, S. Tazawa, and T. Kasai, 1966: A study of the snowfall in the winter monsoon season in Hokkaido with special reference to low land snowfall. *J. Fac. Sci., Hokkaido Univ.*, **11**, 287-308.

Markowski, P., and Y. Richardson, 2010: *Mesoscale Meteorology in Midlatitudes*. Wiley-Blackwell, 407 pp.

Minder, J. R., T. Letcher, L. S. Campbell, P. G. Veals, and W. J. Steenburgh, 2015: The evolution of lake-effect convection during landfall and orogrpahic uplift as observed by profiling radars. *Mon. Wea. Rev*., **143**, 4422–4442.

Umek, L. and A. Gohm, 2016: Lake and orographic effects on a snowstorm at Lake Constance. *Mon. Wea. Rev*., **144**, 4687–4707

Steenburgh, W. J., and L. S. Campbell, 2017: The OWLeS IOP2b lake-effect snowstorm: Shoreline geometry, airmass boundaries, and the mesoscale forcing of precipitation. *Mon. Wea. Rev*., **145**, 2421-2436.

Steenburgh, W. J., S. F. Halvorson, and D. J. Onton, 2000: Climatology of lake-effect snowstorms of the Great Salt Lake. *Mon. Wea. Rev.*, **128,** 709-727.

Veals, P. G., and W. J. Steenburgh, 2015: Climatological characteristics and orographic enhancement of lake-effect precipitation east of Lake Ontario and over the Tug Hill Plateau. *Mon. Wea. Rev*., **143**, 3591-3609.

Veals, P. G., W. J. Steenburgh, and L. S. Campbell, 2018: Factors affecting the inland and orographic enhancement of lake-effect precipitation over the Tug Hill Plateau. *Mon. Wea. Rev*., **146**, 1745–1762.

Veals, P. G., W. J. Steenburgh, S. Nakai, and S. Yamaguchi, 2019: Factors affecting the inland and orographic enhancement of sea-effect snowfall in the Hokuriku Region of Japan. Submitted to *Mon. Wea. Rev*.

Watson, C. D., and T. P. Lane, 2012: Sensitivities of orographic precipitation to terrain geometry and upstream conditions in idealized simulations. *J. Atmos. Sci*., **69**, 1208–1231.