SEA-EFFECT PRECIPITATION

A LOOK AT JAPAN'S "GOSETSU CHITAI"

Adapted from "Perspectives on Sea- and Lake-Effect Precipitation from Japan's 'Gosetsu Chitai,'" by **W. James Steenburgh** (University of Utah) and Sento Nakai. Published in BAMS online January 2020. For the full citable article see **DOI:10.1175/BAMS-D-18-0335.1**.

Portions of Honshu and Hokkaido Islands of Japan experience remarkable snowfalls during the East Asian winter monsoon, when frequent cold-air outbreaks occur over the Sea of Japan (also called the East Sea). Mean annual snowfall in this "Gosetsu Chitai" (heavy snow area) exceeds 600 cm (235 in) in some near-sea-level cities and 1,300 cm (512 in) in some mountain areas. Snow depths can reach 2 m near sea level and 7 m in the mountains, with the snow corridor along the Tateyama Kurobe Alpine Route in the Hida Mountains (a.k.a. northern Japanese Alps) famous for its towering snow walls when it opens each spring. While snowfall is most prolific in Japan, some coastal areas of Korea, Russia, and China observe less frequent but high-impact snowstorms produced by the Sea of Japan or the Yellow Sea.

There is a rich history of cloud microphysical research in Japan and an extensive literature examining sea-effect precipitation and its impacts in Japan and East Asia. But this literature is often overlooked by North American meteorologists. Furthermore, collaborations between Japanese and North American scientists investigating sea- and lake-effect precipitation have been limited. To stimulate such collaboration, we introduce North American meteorologists to the snow climate of western Japan, summarize contemporary knowledge concerning sea-effect precipitation in the region, and make comparisons to lake-effect precipitation of the North American Great Lakes.

Regional climate

Mean sea surface temperatures (SSTs) in the Sea of Japan generally decline westward and poleward, with warmer water where the Tsushima current flows along the west coast of Honshu and colder water where the Liman current flows along the Asian coast. During December, SSTs generally increase eastward from the Asian coast. SSTs decline 2–5°C by February, with the smallest decline near the Sea of Japan coast of Russia and the largest decline near the Sea of Japan coast of north Honshu.

The complex Sea of Japan coast is important in modulating sea-effect precipitation. Downstream, the coastline and terrain of Honshu and Hokkaido are also complex. Central Honshu features the highest peaks and most sustained orography, reaching over 3,000 m above MSL in the Hida Mountains. The terrain of northern Honshu and western Hokkaido is less formidable, but includes numerous peaks over 1,000 m, with some reaching over 2,000 m. The densely populated coastal plains are especially vulnerable to sea-effect snow.

The climate of Japan is often described as monsoonal. Westerly to northerly flow predominates in winter, and southerly to southeasterly flow in summer, with associated variations in precipitation. This seasonal flow reversal reflects the continental-scale circulation changes of the Asian winter and summer monsoon systems, the former featuring the Siberian-Mongolian high over Asia and Aleutian low over the north Pacific. These circulation features result in frequent cold air outbreaks with westerly to northerly flow over the Sea of Japan. The resulting sea-effect precipitation systems share similarities with lake-effect precipitation systems of the Great Lakes, but tend to be deeper, are modulated by higher and more complicated topography, and more frequently feature transverse-mode snow bands.

While the liquid precipitation equivalent (LPE) and snowfall increase dramatically across the Sea of Japan during the East Asian winter (November to March) monsoon, the distribution of these quantities varies considerably depending on location, elevation, and time of year. For example, at Joetsu near the Sea of Japan coast of central Honshu, the

◀* The Sea of Japan (978,000 km²) is about 4 times the area of the Great Lakes and has a maximum northwesterly fetch of ~850 km, compared to ~400 km for Lake Superior. Sea ice typically forms in the Tartary Strait in December and melts in March, covering an average of 3% of the Sea of Japan at its February maximum. In central Honshu (b), mountains reach over 3,000 m above MSL in the Hida Mountains, 2,400 m in the Kubiki Mountains, and 2,000 m in the Echigo Mountains.

mean monthly LPE from November to March is >190 mm and exceeds 400 mm (15.75 in) in December and January. Mean annual snowfall is 635 cm (250 in), with a peak in January. Farther inland at Tsunan in the foothills of the Echigo Mountains, the mean monthly LPE from November to March is lower than Joetsu, but still reaches over 200 mm (7.87 in) in December and January. Mean annual snowfall is 1,349 cm (531 in), with a monthly maximum of 443 cm (174 in) in January, remarkable totals for a site at 452 m above MSL and 37.0° N. Satellite data show that clouds and precipitation produced during potential sea-effect periods comprise a majority of the clouds and precipitation over the Sea of Japan and adjoining regions of Honshu and Hokkaido from December through February.

Sea-Effect Systems

A wide range of cloud and precipitation patterns are produced during cold-air outbreaks over the Sea of Japan and include open-cellular convection, quasi-periodic cloud and precipitation bands aligned parallel to the mean boundary layer flow, or quasi-periodic cloud and precipitation bands aligned normal to the mean boundary layer flow. The latter two patterns are associated with horizontal roll convection, which produces cloud and precipitation bands. Along-flow bands are referred to as “L-mode” in Japan given their longitudinal orientation relative to the mean boundary layer flow. Across-flow bands are called “T-mode” for their transversal orientation to the mean boundary layer flow. The two modes can occur concurrently over the Sea of Japan due to regional variations in boundary layer depth and directional shear during cold-air outbreaks.

L-mode bands are analogous to quasi-periodic wind-parallel bands found over the Great Lakes. T-mode bands appear to be rare over the Great Lakes as they are not identified in climatological studies and there are no case studies describing such bands in the peer-reviewed literature. The reasons for the relative scarcity of T-mode bands over the Great Lakes are unclear.

In addition to boundary layer circulations, the coastal configuration of mainland Asia produces circulations and low-level convergence that can generate broader, more intense cloud and precipitation bands. For example,

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* **The snow corridor along the Tateyama Kurobe Alpine Route. Source: Uryah, Wikipedia Commons, CC BY-SA 3.0.**

the Japan Sea polar airmass convergence zone (JPCZ) can form in response to flow interactions with the Korean Highlands and differential surface heating between the Korean Peninsula and the western Sea of Japan.

Smaller-scale landscape features along the Asian coast also modulate winds, clouds, and precipitation. Mesovortices, polar lows, and associated airmass boundaries are common over the Sea of Japan and affect sea-effect snowfall. In some cases, the JPCZ is a locus for mesovortex genesis. During one winter, five mesovortices were identified during 46 sea-effect events affecting central Honshu. The mesovortices had diameters of 20–100 km and were often accompanied by a curved snowband and wind shift. Mesoscale snow bands generated by the JPCZ can produce heavy snowfall and typically reach higher elevations than other sea-effect systems. Aircraft observations have revealed high ice crystal concentrations reaching $1,000 \text{ L}^{-1}$ and 0.3 g m^{-3} in the well-developed convective cloud region of JPCZ.

Although it is commonly assumed that precipitation and snowfall increase with altitude, sometimes precipitation near the Sea of Japan is heavier in the lowlands and adjoining foothills. These “satoyuki” snowfalls are distinguished from “yamayuki” snowfalls (heavier mountain accumulations). A conceptual model for satoyuki snowfalls includes an inversion near mountain top and clouds confined to the windward lowlands, with heavier,

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* Mean monthly liquid precipitation equivalent (LPE) and snowfall in the Sea of Japan region. Unlike sites on mainland Asia, which observe minimum monthly LPE in December or January, Joetsu and Tsunan in Japan observe maximum LPE in those months. Farther north at Aomori and Sapporo, monthly mean LPE from November to March is lower, but a greater fraction of precipitation falls as snow and the accumulation season is longer. Sukayu Onsen (890 m MSL) in the mountains above Aomori receives 1,764 cm mean annual snowfall, while Kutchan (176 m MSL), near the base of Mt. Niseko, gets a mean of 1,062 cm.

rimed ice crystals such as graupel falling near the coast and lightly rimed crystals falling farther inland. In some instances, katabatic flow develops along the coast, opposes the large-scale flow, and produces or enhances a land-breeze front that generates precipitation near the coast or offshore. For a given flow direction (e.g., 290°), the inland penetration and orographic enhancement of sea-effect precipitation increases with the mean boundary layer

◀* NASA MODIS visible imagery of sea-effect cloud systems on 24 Jan 2012, including bands oriented longitudinally (L) and transversely (T) in the mean boundary layer flow. Mesoscale vortice formation is associated with the JPCZ, a recurring convergence zone.

(i.e., 950–800-hPa) wind speed. Downstream of Lake Ontario and west of the Appalachians, the inland penetration of lake-effect precipitation and enhancement over the 500-m high Tug Hill Plateau similarly increases with the strength of the boundary layer flow.

Graupel is common in sea-effect storms, particularly in L-band snowbands, due to the strong updrafts and large supercooled cloud water concentrations, which leads to accretional growth. The density of graupel particles in sea-effect storms varies significantly, which may cause large uncertainty in quantitative precipitation estimates from radar. The spherical or conical shape of graupel forms snow-pack with a small particle-to-particle contact area, which tends to be less cohesive and can fail, initiating avalanches.

Graupel falls predominantly in coastal areas, producing as much as one-third of the precipitation in central Honshu. Farther inland, less graupel may reflect less surface sensible and latent heating and thus less updraft strength, supercooled liquid water availability, and accretional growth. This would be broadly consistent with the convective-to-stratiform transition that occurs, for example, downstream of Lake Ontario. In some instances, orographic updrafts in Japan can counter this transition and increase graupel production or size.

Snow Hazards

The combination of extreme snowfall and high population density near the Sea of Japan

poses great challenges for public safety, road and sidewalk maintenance, and avalanche mitigation. Although estimates vary, Japan likely averages more than 100 deaths and 400 injuries each year due to snow and ice hazards, with most victims succumbing due to snow-removal activities. The 1963 “gosetsu” (heavy snowfall) winter led to 231 fatalities and 1,735 totally or partially damaged homes nationwide. Snow depths reached 3.18 m in Nagaoka. The 1918 Mitsumata avalanche in the Niigata prefecture killed 155—one of the 10 deadliest avalanches worldwide since the sixteenth century. Russia’s Sakhalin Island east of the Sea of Japan and Kuril Islands east of the Sea of Okhotsk also experience frequent sea-effect snowfalls and, while the population density is low, their per capita avalanche fatality rate is among the highest in the world. Most victims are residents and workers, rather than recreationists.

With mean surface temperatures exceeding 0°C even in January and February, west coast cities of central Honshu use groundwater spraying extensively to melt snow on roads and sidewalks. In Obama City, for example, where the mean annual snowfall is 179 cm

Snow melting and removal using water tubes at the Snow and Ice Research Center in Nagaoka. *
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but the daily mean temperature in January is 3.7°C, efforts to melt snow accounted for 13% of the groundwater usage in 2011. Elsewhere, snow is removed with road and sidewalk heating systems, snow-flowing roadside gutter systems, and snow-melting tanks (such as in Sapporo). The gutter systems drain downslope with river water or warm treated sewage effluent that melts snow dumped through grates by residents. The tanks dispose snow removed from roads, with sewage effluent or heating from waste incineration providing energy for snowmelt.

Japan has extensive road weather information systems, and the Snow and Ice Research Center at the National Research Institute for Earth Science and Disaster Resilience has developed a Snow Disaster Forecasting System (SDFS) for predicting avalanche potential, reduced visibility, road conditions, and snow accretion. The SDFS integrates atmospheric (large-scale and cloud-resolving), snow metamorphism, blowing snow, avalanche, and road-weather models.

Skiers, snowboarders, and Japan's winter-sports economy are major beneficiaries of the extreme snowfall. For example, Sapporo and Nagano each hosted an Olympic Winter Games (in 1972 and 1998, respectively).

Vulnerability to Climate Change

Snowfall at mild, low-elevation sites near the Sea of Japan has declined significantly. From 1962 to 2017, the ratio of annual maximum snow depth relative to the 1981–2010 average declined at a rate of up to 13.8% per decade in western Honshu. Trends appear to be weak or undetectable to date, however, in relatively cold, high-latitude, or high-elevation regions. Similar temperature and altitudinal dependencies are observed in western North America.

◀* The relation of sea-effect with mean 950–800-hPa wind direction of 290° along a NW-SE transect crossing the coast near Joetsu, for (b) mean wind speed $\leq 8.8 \text{ m s}^{-1}$; (d) $11.5\text{--}13.6 \text{ m s}^{-1}$; and (f) and $\geq 16.4 \text{ m s}^{-1}$. Frequency of radar echoes $> 10 \text{ dBZ}$ according to color scale, terrain (grey shaded), mean radar-derived LPE rate (blue line), and gauge LPE rate (circles). From Veals et al. (2019) in *Mon. Wea. Rev.*

BAMS: How did you become interested in sea-effect snow in Japan?

***Jim Steenburgh:** In 1998, the Salt Lake City Organizing Committee for the 2002 Olympic and Paralympic Winter Games sent me to Japan to learn about weather support for the Nagano Winter Olympics. I spent most of my time in Hakuba, which sits at the base of the stunning Hida Mountains, also known as the Northern Alps. I was largely uneducated about the climate of Japan, and I was shocked to find the region so snowy.*

BAMS: What else struck you about Japan’s snow?

***JS:** There are many remarkable aspects about Japan’s Gosetsu Chitai, but what I have found most surprising is just how rapidly the snowfall decreases as you move inland. In 2017, I was staying on the slopes of Mt. Myoko, a 2,400-meter-high peak near the Sea of Japan. It had snowed a ton and the nearby train station was closed, so my hosts drove me to the next train station, which was only 8 km farther inland, but was open. The snow stopped quickly as I rode the train inland.*

BAMS: What were the keys to making this project happen so far from home?

***JS:** The most important thing for this paper and others we are publishing on this topic is*

the relationship we have between my group at the University of Utah and scientists at the Snow and Ice Research Center in Nagaoka, including Sento Nakai, my coauthor for this paper. I contacted Sento by email several years ago to introduce myself, and from that moment, he and his colleagues have been incredible collaborators.

BAMS: Parting lessons?

***JS:** This work was really fun. It shows the value of greater collaboration between scientists and forecasters in North America, Japan, and other sea- and lake-effect regions, as well as the great potential to advance our understanding and prediction of sea- and lake-effect precipitation based on studies from the Sea of Japan region.*

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 * (Left to right)
 Steenburgh and
 Nakai with Peter
 Veals (University
 of Utah) in the
 mountains near
 Nagaoka.

Regional climate modeling studies suggest, however, that snowfall and snowpack will eventually decline at all elevations due in large part to climate change. These results suggest long-term declines in snowfall and snowpack are likely across most of Japan’s Gosetsu Chitai during the twenty-first century, with the largest declines in lower-latitude regions near sea level and the smallest at higher altitudes and latitudes.

Next Steps

There is significant potential to advance our understanding and prediction of sea- and lake-

effect precipitation by strengthening collaborations between scientists in North America, Japan, East Asia, and other sea- and lake-effect regions. In particular, comparison of sea- and lake-effect systems of the world is important for understanding the fundamental processes that control them and their influence on precipitation. Clarifying the regional microphysical differences of sea- and lake-effect clouds may help improve microphysical parameterizations in numerical models and in turn forecasts of sea- and lake-effect phenomena. ●●

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