

# The Cloud Trails of the Hawaiian Isles



Satellite images show puffy cloud trails up to 100-km long in the lee of most Hawaiian Isles. Scientists have thought these trails are due to the trade winds flowing over and around the islands, and then coming together again and rising to form clouds in the islands' wake (Figure 1). The daytime trails, however, dissipate at night, IPRC postdoctoral fellow **Yang Yang** and research team leader **Shang-Ping Xie** discovered. If only wind convergence causes the trails, the trails should be there day and night. The sun's daily cycle must therefore have something to do with their formation also. Intrigued, Yang and Xie applied a computer model to see whether it could be used to study the cloud trails. The model successfully captured the cloud trails, their formation and dissipation. It confirmed the hunch that thermal processes related to daily heating and cooling of the islands combine with the converging winds to create the cloud trails.

Yang, now research meteorologist at the National Institute of Water & Atmospheric Research in New Zealand, has been specializing in observing and modeling Hawai'i rain, clouds, and wind patterns, first for his dissertation research with **Yi-Leng Chen** at

the University of Hawai'i and then with Shang-Ping Xie at the IPRC. In this latest study, the IPRC team consisting of Yang, Xie, and **Jan Hafner** combined satellite analysis with computer modeling. Taking the observations from the polar orbiting MODIS Terra and Aqua and the geostationary GOES-10 satellites, they mapped the summer (June–August) cloud climatology in the vicinity of Ni'ihau, Kaua'i, and O'ahu, and of the island of Hawai'i known as the "Big Island." East-northeast trades with an inversion height of about 1500–2000 m and a typical wind speed of 8 m/s prevail over the islands much of the year. It is well known that the typical trade wind flow-pattern for the Big Island, with mountain peaks rising above 4000 m, differs from that for the islands of Ni'ihau, Kaua'i, and O'ahu with peaks below 2000 m. The lower profile islands have winds flowing directly over the mountains, and the peak mean rainfall is on the highest mountains. With the Big Island, the trade winds tend to flow around the high mountains, and the mountain tops receive very little precipitation. Because of the descending trades, the leeward slopes of the islands are much drier than the windward slopes. Nevertheless, the team's analy-

sis of the satellite images reveals that during early afternoon, cloud cover in specific lee regions can be comparable to that on the windward side.

The satellite analysis, moreover, shows that over the lee sides of the islands of Ni'ihau, Kaua'i, and O'ahu, clouds form by 11 o'clock in the morning, reaching their peak around two o'clock in the afternoon (Figures 1 and 2). Extending from the lee coasts, the cloud trails grow westward for more

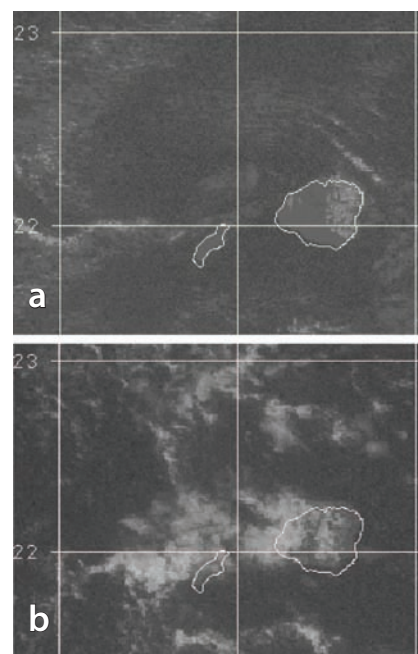
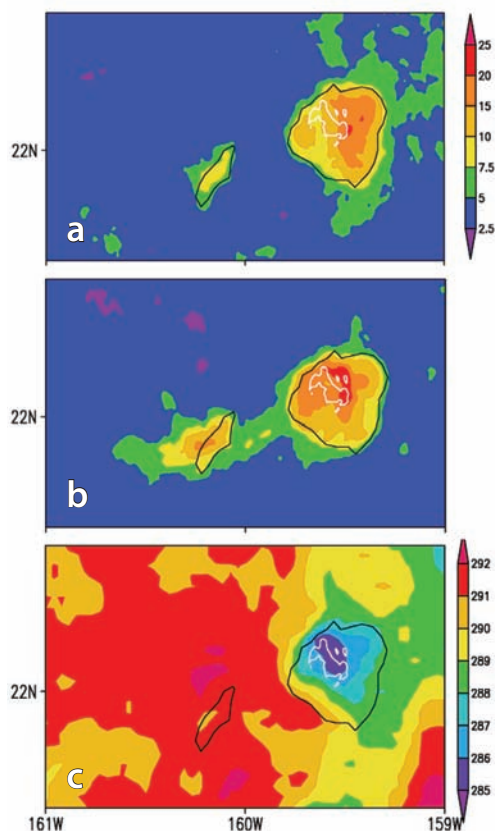


Figure 1. GOES-10 visible images at (a) 10:30 am and (b) 2:15 pm on 5 September 2006.



**Figure 2.** For the island of Kaua'i during August 2005, mean effective albedo (%), indicating reflecting clouds, derived from GOES-10 visible radiance at (a) 11:00 am and (b) 2:00 pm, and (c) brightness temperature (K) derived from the GOES-10 IR channel at 2:00 am Hawai'i Standard Time. Terrain elevation of 1000 m is shown by the white contours; black lines show island outlines.

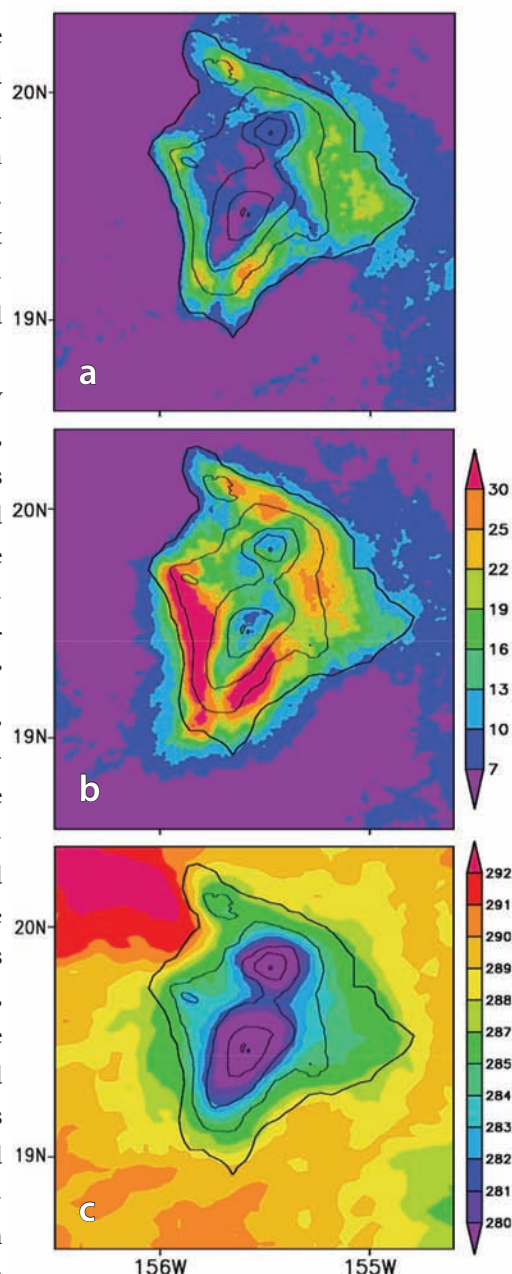
than 70 km over the ocean. In late afternoon, they start to disappear again, but without any obvious westward progression. By two o'clock in the night, the GOES-10 infrared channel shows the cloud bands have dissolved, registering a brightness temperature that is 3–4 K higher over the lee than the windward ocean (Figure 2c).

To confirm their hunch about the thermal mechanism in generating the cloud trails, the team supplemented the satellite cloud study with simulations using the Mesoscale Model of Pennsyl-

vania State University and NCAR, the MM5. The model was coupled with a land surface model that codes the vegetation, soil type and vegetation fraction compiled by the US Geological Survey. Yang and Chen had already shown that the MM5 captures well the overall observed Big Island daily cycle of wind and rainfall.

The team ran the MM5 with daily data from June 1 to August 31, 2005, and analyzed 92, two-hour snapshots of the output. For Kaua'i, O'ahu, and even tiny Ni'ihau, standing below the trade-wind inversion, the MM5 simulates the expected winds flowing over and around the islands; in the islands' wakes, the winds converge and rise, continuing on their southwest journey. As the sun heats the islands, the MM5 shows first the clouds beginning to form over the leeward side and the trades carrying, or advecting, the warmed island-air downstream. As the surface pressure downstream falls, convergence becomes stronger, the warm, moist air rises, condenses, and the cloud trails grow. When the islands cool at night, the MM5 simulates cold air moving downstream from the island and suppressing cloud formation in its path. Atmospheric soundings from a recent cruise survey conducted onboard the University of Hawai'i Research Vessel *Kilo Moana* support this thermal mechanism for the cloud trails.

The satellite images on the lee side of the Big Island, the Kona Coast, show a quite different picture from that of the lower profile islands. Though clouds form along the Kona Coast by 11 o'clock in the morning, further away from the coast, the ocean remains cloud free (Figure 3a). Only by two o'clock in



**Figure 3.** For the Big Island during August 2005, mean effective albedo (%), indicating reflecting clouds, at (a) 11:00 am and (b) 2:00 pm from GOES-10 visible channel, (c) IR temperature at 2:00 am from GOES-10 IR channel-5. Contour interval is 1000 m (black lines; outermost lines show island outlines).

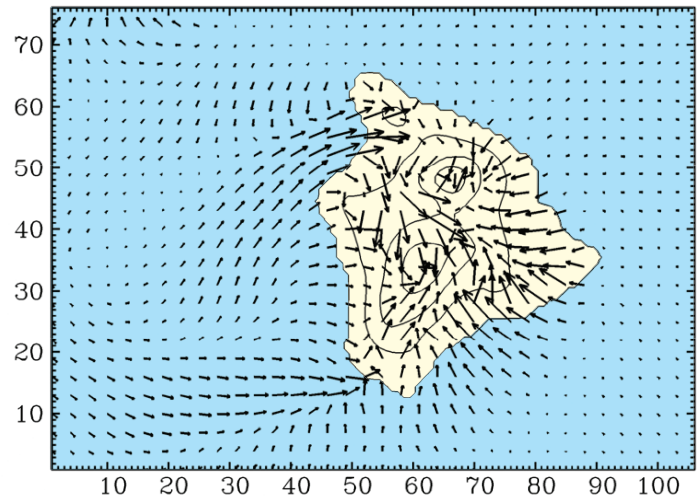
the afternoon do the clouds that have formed along the coast begin to extend out over the ocean, but at the most for 20 km (Figure 3b). At night, the temperatures are lower (284–287 K) in the



wake off the Kona Coast than to the north or to the south (Figure 3c), an indication that a cloud deck has formed there. The nighttime Kona cloud deck is consistent with coastal rain gauge data that registers maximum rainfall in the evening and night for parts of the Kona Coast.

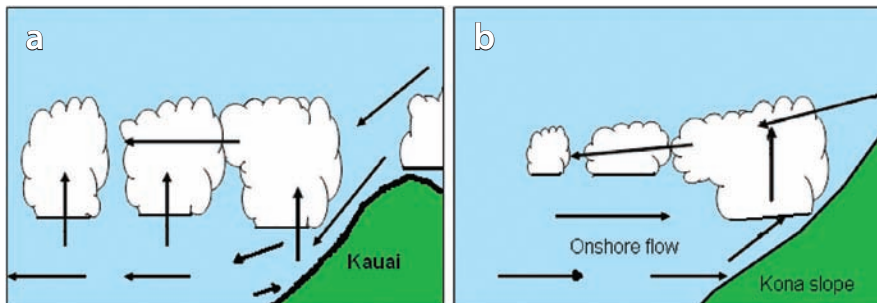
MM5 reproduces clearly how the island's tall mountains and saddles shape the overall Big Island wind and cloud patterns very differently from the other islands. Strong 12–14 m/s easterly winds blow around the southern and northern tips of the Big Island and, in the wake of the island, form the known westerly reverse flow that flows with up to 3 m/s towards the Kona Coast. The westerly return flow reaches about 2000 m high, above which the easterly trades flow. The MM5 also reveals how the daily heating and cooling of the island affects the winds and the clouds. As the sun heats the island, sea breezes strengthen the western reverse flow and carry moist air toward the Kona Coast. Clouds develop on the Kona slope, but the strong day-time reverse flow prevents the generated heat from being transported downstream and forming a cloud trail. During the night, the down draft of trades together with the land breezes blow cold air offshore and encounter the now warmer reverse flow. Consistent with the increased nighttime cloudiness seen in the satellite images, the MM5 has the upward motions form a cloud band extending up to 20 km from the Kona Coast.

The cloud trails tell a further surprising story. Off the southwestern tip of the Big Island, the satellites images do have clouds appearing in the morning, and by afternoon the clouds have grown into a well-defined cloud band that tilts in the southwest direction, stretching for more than 70 km offshore (Figure 3 a and b). This is the first time this diurnal



**Figure 4.** For the Big Island, 2:00-pm minus 2:00-am wind-differences at 50 meters above the surface from MM5 simulations for June–August 2005. The figure shows the wind patterns associated with the south-west cloud band. On the coast near Kauna Point, the rising motion is enhanced in the afternoon by the three-way convergence of the (anomalous) sea breezes/anabatic flow from the west and east slopes of the south extension of Mauna Loa, and from the southwest (perpendicular to the coast between Kauna and South Points). The convergence line extends offshore, separating the anomalous westerlies to the north and the anomalous south-to-southwesterly winds to the south. The formation mechanism for this sharp convergence line probably involves complicated interactions of thermal and dynamical forcing of the island.

cloud trail seen in the satellite images has been recorded in the literature. By 2 o'clock in the early morning, the infrared brightness temperature from GOES-10 is somewhat higher in the region of the southwest tilted band, indicating that the lee southwest cloud band has dissolved (Figure 3c). The MM5 also shows a sharp line of converging winds (Figure 4)



**Figure 5. Schematics of the afternoon winds and cloud formations in the wakes of (a) low-profile Kaua'i and (b) tall Big Island.**

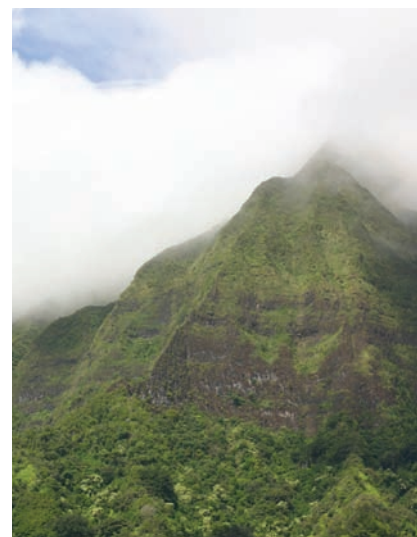
that develops during mid-morning and stretches, as in the satellite images, from the southwestern tip of the Big Island for at least 70 km offshore. The convergence line forms where daytime sea breezes meet the easterly trades (Figure 4), and the line anchors the southwest lee cloud band observed in the satellite images. During night, the MM5 simulates the convergence line weakening substantially and the associated cloud trail dissipating.

On the northwestern tip of the Big Island, the satellite images reveal no cloud trails, and MM5 simulates convergence too weak for cloud formation. A reason for the asymmetry, according to the research team, could be the interaction between the trade winds that become very strong as they are forced around the Big Island and the Coriolis force. This interaction can lead to wind convergence at the southern tip of the wake and divergence at the northern tip.

The MM5 analysis shows how the complex interaction among winds, mountain height, and heating and cooling by the sun affects the daily cycle of

the leeward clouds, favoring the cloud trails seen in the wake of the lower profile islands, but not in the wake of the tall mountains of the Big Island (Figure 5). The clouds stretching from the southwestern tip of the Big Island are formed by a different mechanism.

The Hawaiian Isles make a superb natural laboratory for studying how macro and micro processes work together to create clouds and rainfall: the winds—the sea and land breezes, the trade winds differing in strength from one day to the next, the moisture they carry and the vortices and eddies they form; the varied Hawai'i mountain topography and vegetation, ranging from lush rain forest to barren lava; and the daily heating cycle. This study on the trail clouds is just one example of how high-resolution computer models that adequately resolve the Hawaiian Isle topography can help to understand these many interactions.



This story is based on Y. Yang, S.-P. Xie, and J. Hafner, 2008: *The thermal wake of Kauai Island: Satellite observations and numerical simulations*, *Journal of Climate*, 21, 4568–4586; and Yang, Y., S.-P. Xie, and J. Hafner, 2008: *Cloud patterns lee of Hawaii Island: A synthesis of satellite observations and numerical simulation*. *Journal of Geophys. Res.-Atmos.*, **113**, D15126, doi:10.1029/2008JD009889.

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