9.10 NUMERICAL SIMULATIONS OF THE WAKE OF KAUAI WITH IMPLICATIONS FOR THE HELIOS FLIGHTS

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ABSTRACT

High resolution numerical simulations of the wake of the Hawaiian island of Kauai are performed for various idealized and observed upstream atmospheric profiles. The wake is shown to extend very large distances downstream, and the wake geometry depends on the structure of the upstream wind profile, and to a lesser extent, the height of the trade wind inversion. In most cases, a sharp transition zone in velocity and temperature is observed at the wake boundaries; indeed this transition zone helps to define the wake boundary. The associated shears in the transition zones can be large enough to induce instabilities locally, and cause the wake lateral boundaries to be transitory and turbulent. The instabilities are not observed in the coarser model simulations, indicating the necessity for high resolution (of at least 200 m horizontally) in numerical studies of island wakes. Application of the simulation results will be discussed in the paper.

1. INTRODUCTION

The Helios prototype was an experimental UAV designed to fly long duration flights at high altitudes. Test flights were operated out of the U.S. Navy's Pacific Missile Range Facility (PRMF) on the Hawaiian island of Kauai. During a flight on the morning of 26 June 2003, the Helios experienced control difficulties, suffered some structural failures and was subsequently lost at about 3000 ft MSL elevation at 10:35 HST (2035 UTC) about 10 miles west- northwest of PMRF.

The dominant wind direction at the altitude of the breakup was from the east, but at lower levels it was from the WNW due to a local sea breeze on shore flow (Donohue et al. 2004). Thus throughout most of its flight the Helios was in the downwind wake of Kauai (Ehernberger et al. 2004).

In support of the Helios Mishap Investigation Board (MIB), high-resolution numerical simulations were conducted to investigate the fine scale structure of the flow in the wake of Kauai on the day of the Helios mishap. The wake is shown to extend very large distances downstream, and the wake geometry depends on the structure of the upstream wind profile, and to a lesser extent, the height of the trade wind inversion. In most cases, a sharp transition zone in velocity and temperature is observed at the wake boundaries; indeed this transition zone helps to define the wake boundary. The associated shears in the transition zones can be large enough to induce instabilities locally, and cause the wake lateral boundaries to be transitory and turbulent. In this paper, we present out model configuration, and some examples of the simulated structure of the wake.

2. NUMERICAL MODEL

The numerical model used in this study is documented in Clark (1977) and Clark and Hall (1991). It is a three-dimensional nonhydrostatic finite difference model that employs the anelastic approximation, and is formulated in terms of terrain following coordinates. The sub-grid scale mixing is provided via a first order closure, and moisture is included explicitly using a warm-rain microphysics parameterization. The model is capable of two-way nesting in both

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the horizontal and vertical. The configuration of the model domains are described in Table 1 and shown in Figure 1.

Domain	Nx x Ny x Nz	Δx x Δy x Δz (m)
1	90 x 90 x 100	6000 x 6000 x 200
2	100 x 100 x 110	3000 x 3000 x 100
3	152 x 128 x 100	1000 x 1000 x 100
4	152 x 128 x 100	500 x 500 x 50
5	152 x 128 x 90	167 x 167 x 50

Table 1: Dimensions of the 5 domains used in the numerical simulations.

Numerous simulations were performed to investigate the effect of changing upstream conditions such as wind direction, low-level shear, inversion height etc. In this paper, we present only those results from one simulation. Further results will be presented in a future publication, and at the conference.

3. SIMULATION RESULTS

The simulation that is the focus of this paper uses the 1200 UTC 26 June 2003 sounding from Lihue (PHLI) to initialize the model. (This sounding is presented in Fig. 2 in Skew-*T* format.) Lihue is on the south-east coast of Kauai at 21.97°N, 159.35°W. The sounding features low-level east-northeasterly trade winds of about 6 m/s strength. Above the trade wind inversion (~ 1500 m), the flow eventually reverses to southwesterly. In regions where the terrain height is greater than zero (i.e., not ocean), the surface is heated. The model is integrated for two hours before sunrise (0600 local time), then for four more hours which is equivalent to 1000 local time.

A horizontal cross-section of the wind speed at 1000 local time from Domain 3 (Δx = 1 km) is shown in Figure 3. This figure shows that the wake of Kauai is bounded by two horizontal shear zones. Each shear line is oriented approximately east-west, extends far downstream, and has a wind speed differential of approximately 6 m/s across its width. Eventually, these two shear lines join, defining the downstream extent of the wake. Within the shear line, there exists non-zero sub-grid turbulent kinetic energy, this is due to low Richardson number in those locations. Within the wake, i.e., between the shear lines, the flow is relatively weak, with some westerly flow recirculation with ~ 1-2 m/s speed.

Zonal and meridional cross-sections through Domain 3 (Figs. 4 and 5) show that the wake has a complicated structure in all spatial directions. First, the zonal cross section shows that the northern-most shear line is lower in altitude closer to the island, and increases in altitude downstream. This figure also shows that the low-level re-circulating flow is relatively shallow, with the peak in the westerly flow being close to the surface. This westerly flow exists in simulations without surface heating also, but is enhanced by the sea breeze in this simulation.

Figure 5 shows the meridional structure of the shear lines downstream of the island. As altitude is increased, both shear lines tilt towards the north. The northern shear line tilts more to the north than the southern shear line, and is more coherent. The tilt of the shear lines with height was present in numerous of the simulations. Simulations using idealized upstream conditions showed that the tilt of the wake was related to the low-level directional shear that is present in the Lihue sounding. The asymmetric topography is also partly responsible for the asymmetry between the northern and southern shear lines. The tilt of the wake also results in strong vertical shear as well as horizontal shear.

The results from Domain 3 (Δx = 1 km) presented above show the shear lines to be relatively smooth, and quasi-steady. This is not the case in higher-resolution simulations. Figure 6 shows simulation results from Domain 5 (Δx = 167 m), focusing on the northern shear line. In this high-resolution domain, the wake is no longer smooth and quasi-steady. Rather, the higher resolution has allowed the horizontal and vertical shears to strengthen to the point that they are dynamically unstable. The shear lines therefore break down due to Kelvin-Helmholtz instability, and form turbulent and transient eddies. These turbulent eddies are advected both downstream along the shear line, and into the re-circulating flow within the wake. The instability in the shear lines is not present in any of the coarser domain simulations.

4. SUMMARY

The structure of the wake of Kauai has been investigated using numerical simulations. In the simulations the wake is bounded by two shear zones which contain the velocity deficit region of the wake and have a complicated geometric structure. The magnitude of the shear within these zones is sufficient to induce instabilities of the Kelvin-Helmholtz type, and subsequently the shear lines break down into transient eddies. At the conference, the results of other simulations will be presented that highlight the role of the upstream conditions in determining the wake structure, including its geometry and its turbulence.

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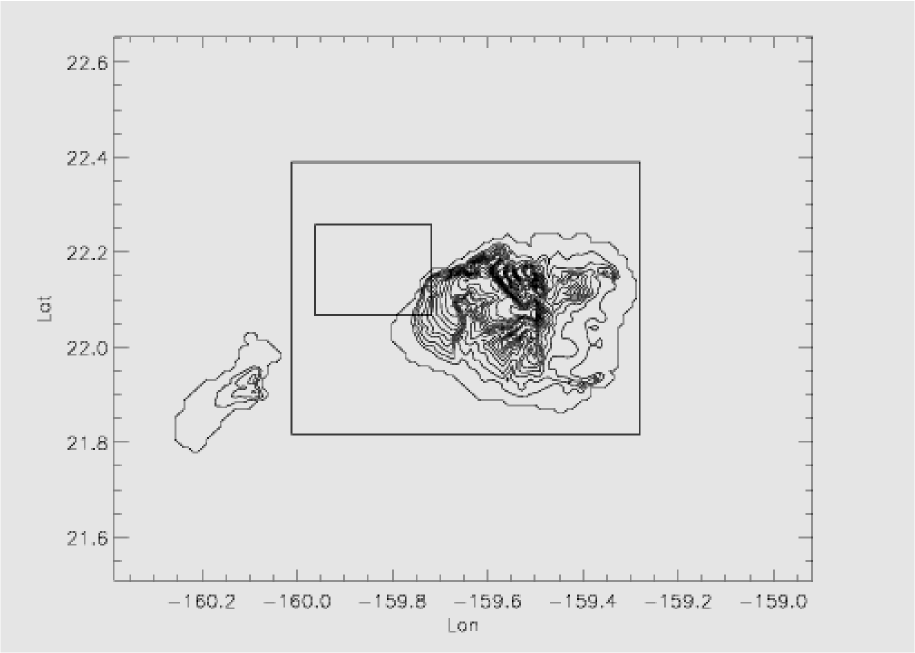

Figure 1: Domain configuration for the numerical model. The topography on Domain 3 is shown with 100 m contours, also shown is the outline of Domain 4 (∆x=500 m) and Domain 5 (∆x=167 m).

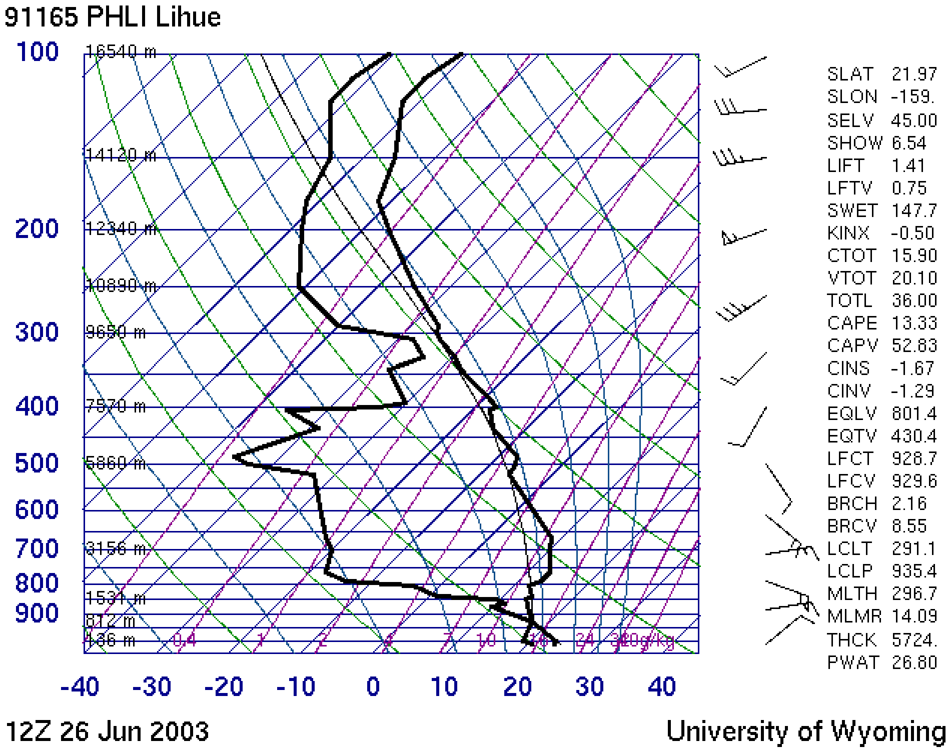

Figure 2: The 1200UTC 26 June 2003 Lihue sounding (Courtesy of University of Wyoming).

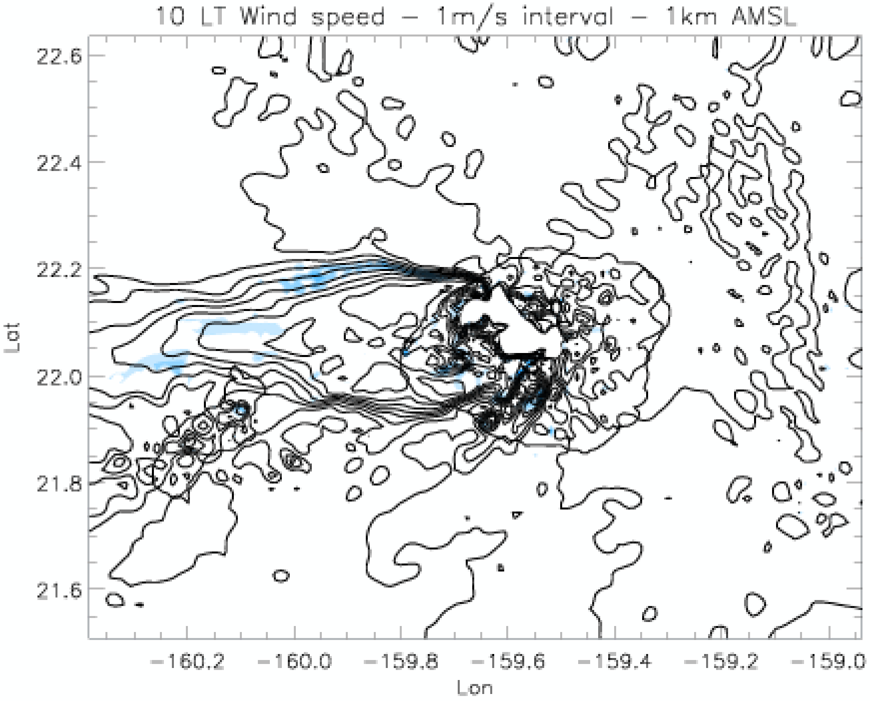

Figure 3: Contours of wind speed at 1 km above mean sea level from Domain 3. Contours are at 1 m/s interval. Also shown is sub-grid turbulent kinetic energy (blue shading), and the coastline (thick line).

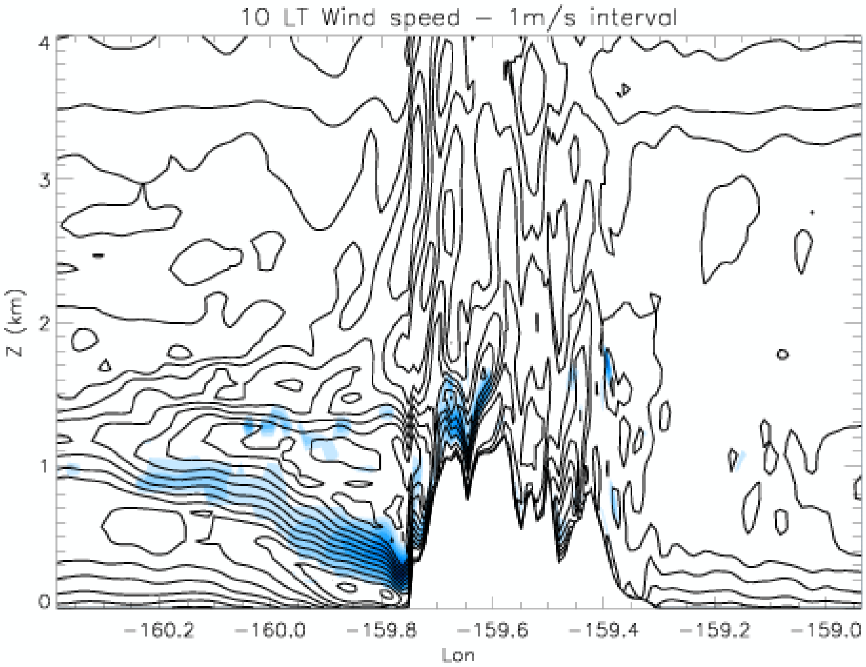

Figure 4: Zonal cross-section of wind speed (1 m/s interval) and sub-grid TKE (blue shading). The outline of Kauai is also shown (thick line). The cross-section passes through the northern shear line.

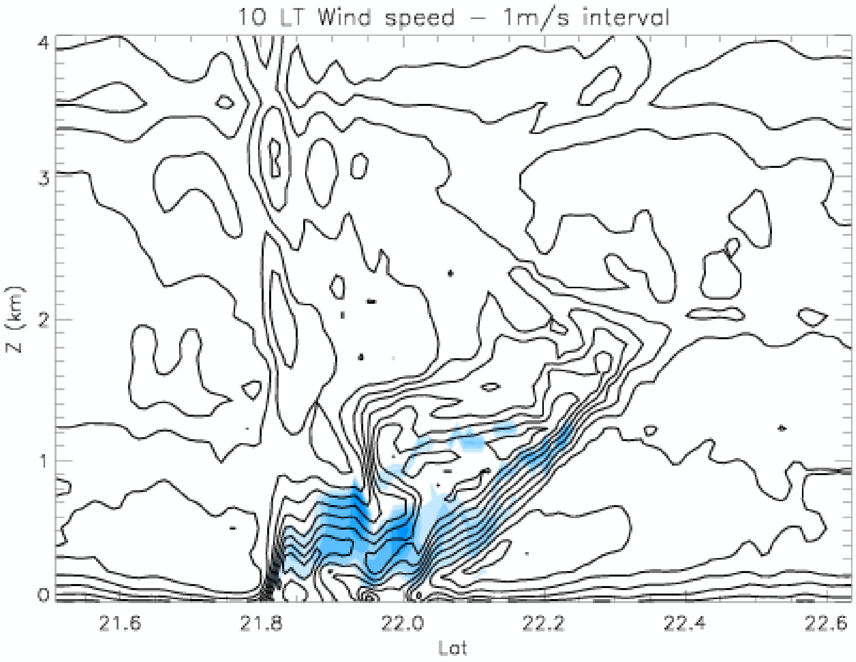

Figure 5: Meridional cross-section of wind speed (1 m/s interval) and sub-grid turbulent kinetic energy (blue shading). The cross section is about 15 km downstream of Kauai.

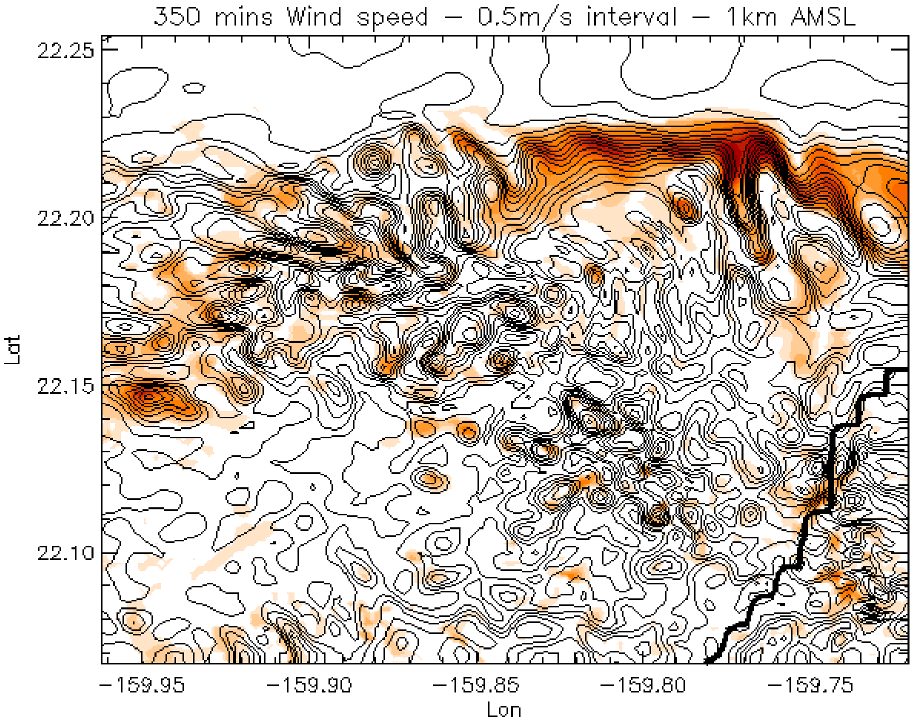

Figure 6: Contours of wind speed (0.5 m/s interval) and sub-grid TKE (red shading) at 1 km above sea level from Domain 5 at 0950 local time.