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Wave breaking induced surface wakes and jets observed during a bora event

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[1] An observational and modeling study of a bora event that occurred during the field phase of the Mesoscale Alpine Programme is presented. Research aircraft in-situ measurements and airborne remote-sensing observations indicate the presence of strong low-level wave breaking and alternating surface wakes and jets along the Croatian coastline over the Adriatic Sea. The observed features are well captured by a high-resolution COAMPS simulation. Analysis of the observations and modeling results indicate that the long-extending wakes above the boundary layer are induced by dissipation associated with the low-level wave breaking, which locally tends to accelerate the boundary layer flow beneath the breaking. Farther downstream of the high peaks, a hydraulic jump occurs in the boundary layer, which creates surface wakes. Downstream of lower-terrain (passes), the boundary layer flow stays strong, resembling supercritical flow. **Citation:** Jiang, Q., and J. D. Doyle (2005), Wave breaking induced surface wakes and jets observed during a bora event, *Geophys. Res. Lett.*, *32*, L17807, doi:10.1029/2005GL022398.

1. Introduction

[2] The bora, which is a cold northeasterly wind that develops in the lee of the Dinaric Alps along the Adriatic coast of Croatia, has been the subject of dozens of studies. Many of these studies [e.g., *Smith*, 1985; *Klemp and Durran*, 1987] were based on or motivated by the first comprehensive field observation of the bora that occurred during the Alpine Experiment (ALPEX) in 1982 [*Smith*, 1987]. These studies suggested that the bora flow shares some common characteristics with downslope windstorms and transcritical hydraulic flows.

[3] In the fall of 1999, a bora event was documented by two research aircraft during the 15th Intensive Observational Period (IOP 15) of the Mesoscale Alpine Programme (MAP) [*Bougeault et al.*, 2001]. The objective of the flight was to study the structure of the potential vorticity banners (PVBs) downstream of the Croatian coastal ridge. The concept of terrain-induced PVBs was first proposed by *Smith* [1989]. He argued that potential vorticity could be generated in the lee of mountains by wave-breaking (or hydraulic jump) related internal dissipation or surface friction. This hypothesis has been supported by a number of numerical studies [e.g., *Schär and Smith*, 1993; *Schär and Durran*, 1997; *Jiang and Smith*, 2003, hereinafter referred to as JS03] and observational investigations [*Jiang et al.*, 2003; *Schär et al.*, 2003; *Flamant et al.*, 2004; *Grubišić*, 2004]. The recent advances in remote sensing technology and high-resolution numerical modeling associated with MAP have provided an unprecedented opportunity to advance our understanding of topographic flows beyond that established based on ALPEX, especially with regard to flow structure below mountaintops.

[4] Recently, *Grubišić* [2004] investigated the dynamics of the secondary PVBs associated with the 7 November 1999 bora event and found that the secondary PVBs are well correlated with the upwind peaks and passes along the Croatian coastline. In a more recent bora study, *Gohm and Mayr* [2005] found that the surface wakes were created by boundary layer separation forced by trapped waves aloft. The objective of this short article is to examine the relationship between the wave breaking in the lower-troposphere and the near surface wind response, including surface jets and wakes over the Adriatic Sea during the 7 November 1999 bora event. It is well understood that surface wind stress torque associated with the jet and wake pattern plays an important role in driving ocean surface currents such as in the Adriatic sea basin [e.g., *Pullen et al.*, 2003].

2. Description of Observations and Numerical Simulation

[5] On 7 November 1999, strong bora winds developed in the lee of the Dinaric Alps and extended over the Adriatic Sea, partially in response to a cut-off process taking place over the Mediterranean, which led to a cyclogenesis over the Tyrrhenian Sea. Real-time numerical models forecasted the formation of PVBs downstream of the Croatian coastal ridge in the morning of 7 November 1999. During the 1300–1800 UTC time period, two research aircraft flew over the Croatian coastal area and the Adriatic Sea to sample PVBs [*Bougeault et al.*, 2001]: the National Center for Atmospheric Research (NCAR) Electra equipped with flight level instruments, down-looking Scanning Aerosol Backscatter Lidar (SABL), and dropsondes, and the National Oceanic and Atmospheric Administration (NOAA) P-3 aircraft equipped with flight-level instrumentation, C-band research radar, and dropsondes. As shown in Figure 1, the Electra flew two crosswind transverses along the coastline and four cross-mountain

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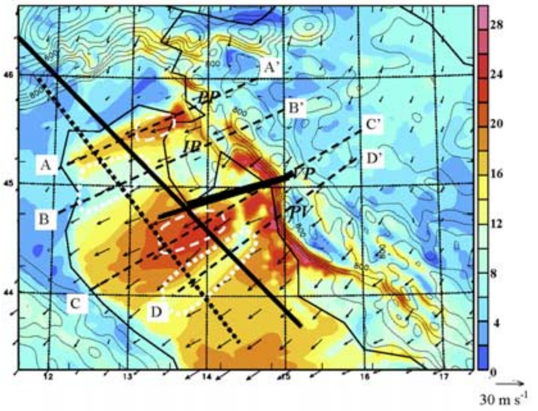

Figure 1. The horizontal wind speed (m s^{-1}, in color) and wind vectors at the 10-m level, derived from the 3-km grid, with terrain contours (interval = 200 m) superposed. The approximate NCAR Electra and NOAA P-3 flight tracks are indicated by bold and dotted straight lines respectively (only two of four Electra cross-ridge tracks are included). The dashed-white curves highlight zones with P-3 belly Radar echoes larger than 34 dBZ and the dotted-white curves highlight zones with P-3 belly Radar echoes weaker than 26 dBZ. Key geographic points of interests are labeled. PP: Postojna Pass, VP: Vratnik Pass, IP:Istra Peninsula, PV: peak Velebit. The four dashed lines (A–A′, B–B′, C–C′, D–D′) indicate locations of the cross-sections shown in Figure 3.

transverses approximately along the low-level wind direction. The P-3 flew crosswind transverses, which are approximately parallel to the Electra crosswind transverses and located further downstream [*Grubišić*, 2004].

[6] The atmospheric component of the Coupled Ocean/Atmospheric Mesoscale Prediction System (COAMPS$^{®}$ (COAMPS is a registered trademark of the Naval Research Laboratory)) is used for this study [*Hodur*, 1997]. COAMPS is a fully compressible, nonhydrostatic and terrain-following mesoscale model featuring a suite of physical parameterizations. The computational domain for the present study is configured with four horizontally nested grids of horizontal spatial resolution 27, 9, 3, and 1 km. There are 55 vertical levels and the terrain-following coordinate is stretched with higher resolution near the surface. The model top is at 31 km with Rayleigh damping applied to the upper 11 km. Initial and boundary conditions are specified using Naval Operational Global Atmospheric Prediction System (NOGAPS) analysis and forecast fields. The topographic data are obtained from a 1-km resolution global dataset.

3. Low-Level Wave Breaking

[7] The COAMPS simulated 10-m wind field shows that the surface wind speed is fairly weak upstream of the coastal mountain range (Figure 1). Flow acceleration occurs over the lee-slope of the Dinaric Alps. Over the Adriatic Sea, the alternating surface jet and wake pattern is evident. The two prominent surface jets are located downstream of the Postojna Pass and the Vratnik Pass, and the two prominent surface wakes are located downstream of the Istra Peninsula and Velebit respectively. The simulated surface jets (wakes) are well correlated with the strong (weak) P-3 belly radar maximum (minimum) echoes (dashed white lines in Figure 1). The vertical motion, zonal wind component, turbulence kinetic energy (TKE), and the corresponding vertical sections of SABL backscatter along two Electra cross-mountain transverses (Figure 1) are shown in Figure 2. The two transverses, executed at 1615-1635 and 1705-1719 UTC respectively, and approximately at the 2.5 km level, are close to each other and oriented approximately along the low-level wind direction. The TKE is computed from the 25-Hz dataset following *Jiang and Doyle* [2004]. Strong vertical motion is present in the lee of the coastal ridge. The maximum vertical velocity derived from the 25-Hz and 1-Hz datasets are 9.4 and 6.9 m s^{-1}, respectively, implying the high-frequency nature of the vertical motion. Along each transverse, there are two major TKE maxima, likely induced by wave breaking over the ridge slope and islands Cres and Krk respectively. The turbulence encountered along the second transverse is much stronger. Near the large TKE zone, a rapid decrease of wind speed is encountered along the flight path. The COAMPS simulation captures the strong turbulence zone and sharp velocity gradient.

[8] In Figures 2c and 2d, the most intense SABL backscatter is apparently due to the scattering by cloud liquid water or reflection from sea or ground surface and the moderate backscatter (yellow) likely corresponds to thin clouds or sea spray. If we assume that the flow is steady and adiabatic, the isentropes should be approximate streamlines. Figure 2 shows that in general the isentropes are consistent with the SABL backscatter patterns. For example, the 288 K contour approximately follows the top of the sea spray layer. Over the lee-slope of the coastal ridge, the descent of the isentropes are gentler than the cloud edge, which is consistent with the phase lag of the simulated TKE patterns (Figure 2) and may also be partially due to the cooling associated with evaporation. Pronounced backscatter minima (shown as blue) appear in the lee of the coastal ridge and the island Krk, likely due to the strong descent which dissipates clouds and thins the sea-spray layer. Over the two islands, the simulated wave crests match the cloud patterns very well, except that the SABL documents some fine-scale structures with horizontal scale of 2 km or smaller, which is consistent with the second TKE maximum at the flight level, and likely associated with shear instability. In the lee of the coastal ridge, the simulated isentropes indicate strong flow descent and subsequent sharp ascent within a short horizontal distance (~10 km), the structure of which resembles a hydraulic jump. All of the key observed features, strong descent and sharp re-ascent pattern, large TKE zone, and sharp deceleration of the cross-mountain wind component, consistently point to the presence of intense low-level wave breaking along the lee slope of the coastal ridge. The COAMPS real-data simulation shows satisfactory agreement with both in-situ measurements and remote-sensing observations, which provides a basis for further analysis of the surface wake and jet patterns.

4. Boundary Layer Flow Response

[9] Four vertical cross-sections of potential temperature, wind speed and turbulence kinetic energy, derived from the

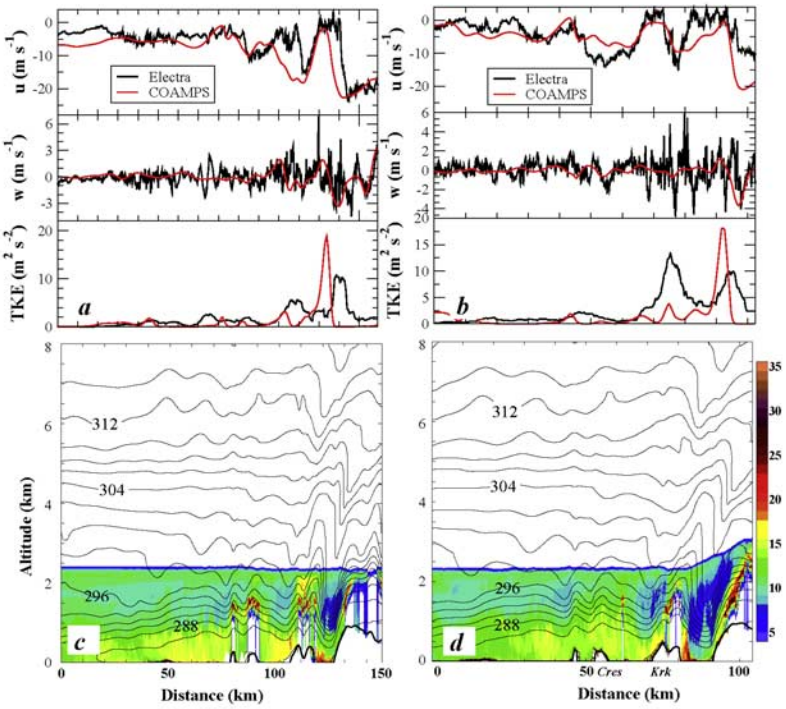

Figure 2. (a) Zonal wind component, vertical motion, and turbulence kinetic energy derived from the Electra flight-level data sampled along the second cross-mountain transverse. The wind fields are from 1-Hz data and the TKE is computed from the 25-Hz data. The red curves correspond to the COAMPS simulated fields obtained by interpolating the 1-km grid data to the straight line through the starting and ending points of the true flight track; (b) same as Figure 2a except for the fourth transverse; (c) vertical cross-section of SABL backscatter (dBz) along the second cross-mountain transverse with terrain (bold curve) and potential temperature contours (contour interval = 2 K) derived from the COAMPS simulation superposed. The COAMPS 1-km grid data is interpolated to the flight latitude-longitude at approximately the flight time; (d) same as Figure 2c except for the fourth cross-mountain transverse.

COAMPS 3-km grid data valid at 1700 UTC and oriented along four cross-ridge lines (i.e., A–A′, B–B′, C–C′, and D–D′ in Figure 1), are shown in Figure 3. Lines A–A′ and C–C′ are oriented through the Postojna and Vratnik passes and the downstream jets, and lines B–B′ and D–D′ are located across the Istra Peninsula and the Velebeit Peak respectively and oriented along the surface wakes.

[10] Apparently, low-level wave breaking occurs in all four sections downstream of the coastal ridge irrespective of peaks or gaps, indicated by sharp descent-and-re-ascent of the isentropes, presence of TKE maxima, and sharp flow deceleration above the boundary layer. However, the low-level wave breaking does not penetrate the boundary layer; instead, it significantly enhances the boundary layer flow and the boundary layer top strongly descends accordingly. Downstream of the passes, the fast flow layer is much deeper than that downstream of the higher terrain, and the strong surface flow extends farther downstream with relatively gradual deceleration. Much stronger flow descent occurs in the lee of Velebeit associated with the steep lee-side slope. The fast and shallow boundary layer flow only extends approximately 25-km downstream where deceleration occurs simultaneously with the ascent of isentropes, the structure of which resembles an internal hydraulic jump within the boundary layer. Multiple wave breaking zones are present over the lee-slope of the Istra Peninsula above the boundary layer, corresponding to the multiple peaks underneath. Near the surface, sharp deceleration of the thin boundary layer flow occurs in the lee of the last peak and the isentropes ascend accordingly in a manner similar to a hydraulic jump. Compared with sections A–A′ and C–C′, the much stronger wave breaking in section B–B′ is likely related to the interaction between the gravity waves forced by the multiscale terrain underneath [*Jiang and Doyle*, 2004].

[11] Clearly COAMPS indicates that the development of the bora winds during this event is associated with the low-level wave breaking. The presence of a flow stagnation zone induced by the low-level wave breaking above the strong downslope winds bears a remarkable analogy to the Smith hydraulic model [*Smith*, 1985]. However, the Smith model does not characterize the flow behavior downstream of terrain. An alternative interpretation can be obtained using two-layer hydraulic theory. In this case, we assume a two-layer structure to the lower troposphere such that the lower layer is represented by the boundary layer flow below the 290 K isentrope, and the flow between 290–300 K corresponds to the upper layer, which is characterized by greater static stability than the lower layer (Figure 3). Above these two layers (i.e., above 300 K), the easterly component is weak, and so is the wave response. According to JS03, two-layer hydraulic flows fall into one of the three states separated by the critical curve $(F_1^2 - 1)(F_2^2 - r) = r^2$, namely supercritical to the external wave mode (PP), subcritical to external and supercritical to internal

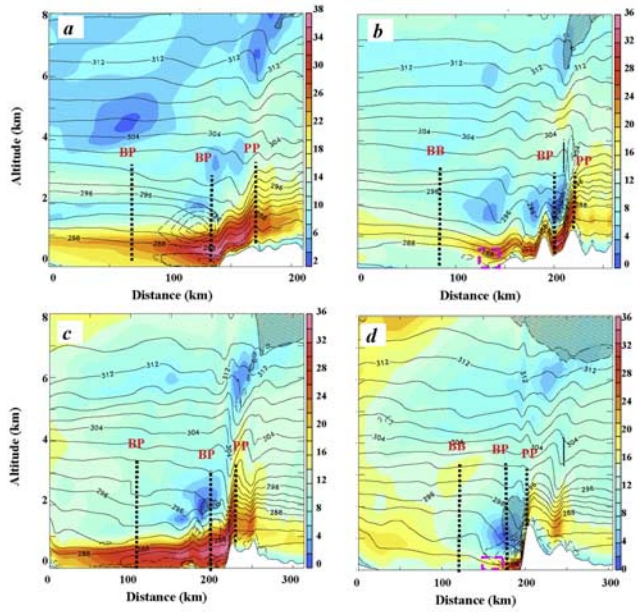

Figure 3. Vertical cross-sections of potential temperature (interval = 2 K), horizontal wind speed (m s^{-1}, color shading), and TKE (dashed contours, interval = 2 m^2 s^{-2}) along lines (a) A–A′, (b) B–B′, (c) C–C, and (d) D–D′ (see Figure 1 for locations). Regions with flow reversed toward upstream are hatched. The Froude numbers at the locations indicated by the dotted vertical lines are estimated and the corresponding flow states are labeled. Following JS03, PP, BP, and BB correspond to externally supercritical, internally supercritical but externally subcritical, and internally subcritical states respectively. The location of the boundary layer jump is indicated by a pink rectangle in Figures 3b and 3d.

mode (BP), and subcritical to internal mode (BB). Here F_1, F_2 are the Froude numbers in the lower and upper layer, and r is density jump ratio defined as $r = (\theta_m - \theta_b)/(\theta_t - \theta_b)$, where θ_b, θ_m, and θ_t correspond to the potential temperature along the bottom, the lower interface, and the top of the second layer. If the two-layer flow is supercritical with respect to the external wave mode (i.e., PP), wave breaking (or external hydraulic jump) could occur initially in the upper layer, which subsequently accelerates the flow in the lower layer and the interface between the two layers descends accordingly. Due to the fast flow in the lower layer, the two-layer system is still supercritical relative to the internal wave mode (i.e., BP) until a second hydraulic jump occurs with expansion and deceleration in the lower layer. The flow response in the lee of Velebeit and the Istra Peninsula is in reasonable agreement with this theoretical interpretation. Downstream of the upper layer jump in the lee of the passes, the second (lower-layer) jump is missing so that the boundary layer flow is free from internal dissipation. We can estimate the internal wave speed in a two-layer system using the simulated potential temperature profiles following JS03. Using r = 0.5 and the reduced gravity $g' = g\Delta\theta/\bar{\theta}$, where $\Delta\theta = (\theta_t - \theta_b)/2 \cong 8K$ [*Durran and Klemp*, 1987], and $\bar{\theta} = 300K$ is the mean potential temperature, the estimated flow states are labeled in Figure 3. As expected, along all four cross sections, flows upstream of the wave breaking zones are externally supercritical, and become externally subcritical and internally supercritical immediately downstream of the wave breaking zones. Farther downstream, the upper layer is much less active, and the lower layer is internally subcritical in the surface wakes and internally supercritical in the jets. The supercritical response of the boundary jet was observed by SABL. The flight transverses shown in Figure 2 are approximately oriented along the Vratnik jet. Over the islands, the simulated isentropes and the SABL observed cloud and sea spray patterns suggest 'supercritical' responses; the wave crests are in-phase with the islands below.

5. Conclusions

[12] An observational and modeling study of a strong bora event is presented with a focus on the connection between gravity wave breaking aloft and the surface jet and wake formation. Strong vertical motion and turbulence were observed in the lee of the Croatian coastal ridge by two research aircraft in the presence of backward vertical wind shear and strong low-level internal wave breaking. The wave breaking occurred above the boundary layer and significantly accelerated the boundary layer flow. The dynamical response of the flow can be interpreted generally by using the Smith hydraulic model [*Smith*, 1985] or a two-layer hydraulic jump theory (JS03). Above the boundary layer, the dissipation associated with wave-breaking induced turbulence creates regions with nearly stagnant flow. The variation of the turbulence strength as a function of the Croatian coastal ridge height leads to a potential vorticity flux and generation of potential vorticity banners [*Grubišić*, 2004]. Associated with the stronger wave breaking in the lee of the Istra Peninsula and Velebeit, the fast boundary layer flow is thinner and more supercritical, and subsequently more conducive for the generation of a boundary layer jump, which creates a long-extensive surface wake. In the lee of the passes, the fast boundary layer flow is much deeper and less supercritical than the flow downstream of the higher peaks, which enables the flow to maintain its speed in the absence of a boundary layer jump.

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References

Bougeault, P., P. Binder, A. Buzzi, R. Dirks, R. Houze, J. Kuettner, R. B. Smith, R. Steinacker, and H. Volkert (2001), The MAP special observing period, *Bull. Am. Meteorol. Soc.*, *82*, 433–462.

Durran, D. R., and J. B. Klemp (1987), Another look at downslope windstorms, part II, *J. Atmos. Sci.*, *44*, 3402–3412.

Flamant, C., E. Richard, C. Schar, R. Rotunno, L. Nance, M. Sprenger, and R. Benoit (2004), The wake south of the Alps: Dynamics and structure of the lee-side flow and secondary potential vorticity banners, *Q. J. R. Meteorol. Soc.*, *130*, 1275–1304.

Gohm, A., and G. J. Mayr (2005), Numerical and observational case-study of a deep Adriatic bora, *Q. J. R. Meteorol. Soc.*, *131*, 1363–1392.

Grubišić, V. (2004), Bora-driven potential vorticity banners over the Adriatic, *Q. J. Meteorol. Soc.*, *130*, 2571–2603.

Hodur, R. M. (1997), The Naval Research Laboratory's Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS), *Mon. Weather Rev.*, *125*, 1414–1430.

Jiang, Q., and J. D. Doyle (2004), Wave breaking over the central Alps: Role of complex terrain, *J. Atmos. Sci.*, *61*, 2249–2266.

Jiang, Q., and R. B. Smith (2003), Gravity wave breaking in two-layer hydraulic flow, *J. Atmos. Sci.*, *60*, 1159–1172.

Jiang, Q., R. B. Smith, and J. D. Doyle (2003), The nature of the mistral: Observations and modeling of two MAP events, *Q. J. Meteorol. Soc.*, *129*, 857–876.

Klemp, J. B., and D. R. Durran (1987), Numerical modeling of Bora winds, *Meteorol. Atmos. Phys.*, *36*, 215–227.

Pullen, J., J. D. Doyle, R. Hodur, A. Ogston, J. W. Book, H. Perkins, and R. Signell (2003), Coupled ocean-atmosphere nested modeling of the Adriatic Sea during winter and spring 2001, *J. Geophys. Res.*, *108*(C10), 3320, doi:10.1029/2003JC001780.

Schär, C., and D. R. Durran (1997), Vortex formation and vortex shedding in continuously stratified flows past isolated topography, *J. Atmos. Sci.*, *54*, 534–554.

Schär, C., and R. B. Smith (1993), Shallow-water flow past isolated topography. part I: Vorticity production and wake formation, *J. Atmos. Sci.*, *50*, 1373–1400.

Schär, C., M. Sprenger, D. Luthi, Q. Jiang, R. B. Smith, and R. Benoit (2003), Structure and dynamics of an Alpine potential vorticity banner, *Q. J. Meteorol. Soc*, *129*, 825–856.

Smith, R. B. (1985), On severe downslope winds, *J. Atmos. Sci.*, *42*, 2597–2603.

Smith, R. B. (1987), Aerial observations of the Yugoslavian bora, *J. Atmos. Sci.*, *44*, 207–269.

Smith, R. B. (1989), Hydrostatic airflow over mountains, *Adv. Geophys.*, *31*, 1–41.

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