THE EFFECT OF WIND DIRECTION ON FLOW PAST SOUTH GEORGIA

H. Wells [1], S. Webster [1], A. N. Ross [2] and A. R. Brown [1]

[1] Met Office, FitzRoy Road, Exeter, EX1 3PB, United Kingdom
[2] University of Leeds, Environment, School of Earth and Environment, Leeds, LS2 9JT, United Kingdom
E-mail: helen.wells@metoffice.gov.uk

Abstract: A series of simulations of idealized flows past South Georgia are conducted in order to investigate how the wind direction affects the airflow around a real mesoscale mountain. Our experiments build on the work of Petersen et al. (2003) who investigated the impact of upstream wind direction on flow around an idealized mountain designed to be a similar size to Greenland. However, our experiments differ from Petersen's experiments in two key ways. Firstly, we use real, complex multi-scale orography rather than idealized, smooth orography. Secondly, our mountain is much smaller. Results indicate that the flow features are sensitive to the wind direction, with the flow most effectively blocked when the incident flow at a slight angle to the major axis of the orography. In contrast to Petersen's experiments around symmetrical idealized orography the flow features are also sensitive to a 180° rotation of the orography. However, the magnitude of the surface pressure force is relatively insensitive to this, varying by less than 10% when the orography is rotated by 180° from any initial orientation.

***Keywords** – Drag, Flow blocking, Barrier Jet*

1. INTRODUCTION

In the last decade the main improvements to the representation of unresolved orographic effects in forecast and climate models have been obtained by improving the representation of physical processes such as low-level flow blocking. The way in which the sub-grid scale orography (SSO) is specified has received much less attention. Typically SSO is specified by a limited number of parameters which describe the shape and variability of the orography in each grid box. This pragmatic approach makes the problem tractable. However, it is unclear whether it can adequately capture the effect of wind direction on the drag. To begin investigating this issue we have performed numerical simulations of idealized flows past South Georgia with different incident wind directions. We chose to use South Georgia (shown in Fig. 1) because it is an example of complex, isolated, anisotropic, mesoscale orography. There are two main peaks both located towards the northern end of the island, which is generally higher than the southern end of the island (throughout this abstract 'north' will be used to refer to the direction pointing towards to top of the figures and 'south' to the opposite direction). The maximum height of the orography is about 1800m.

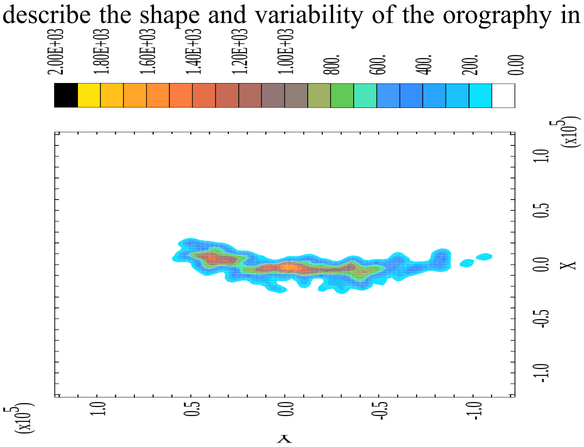

Figure 1: The Orography of South Georgia with the coloured contours indicating height above sea level in metres.

2. EXPERIMENTAL SETUP

The numerical simulations were run using the three-dimensional, non-hydrostatic BLASIUS model described in Wood and Mason (1993). The model was run with 60 levels in the vertical with a grid-spacing of 20m near the surface, increasing to around 1000m near the model lid at 30km. To minimize the reflection of upward propagating gravity waves a Rayleigh damping layer was placed in the upper portion of the domain (from 12km up to the model lid). The horizontal resolution was 2km.

The simulations had a free-slip lower boundary condition and no turbulence scheme (a sensitivity test revealed that the drag and flow fields were relatively insensitive to the lower boundary condition). The lateral boundary conditions were bi-periodic, however the domain was designed to be sufficiently large that perturbations did not wrap around by the end of the 20,000s simulation (non-dimensional time $t^*=Ut/W=5$) so the simulations are not sensitive to the choice of lateral boundary conditions.

The upstream wind speed was constant with height ($U=10ms^{-1}$) and in geostrophic balance. The upstream stability was also held constant ($N=0.01s^{-1}$). The simulations were performed on an f-plane with the Coriolis parameter, $f=0.0001s^{-1}$ (note that this is a northern hemisphere value even though South Georgia is in the southern hemisphere) The maximum non-dimensional mountain height $h_{m*}=Nh/U=1.8$ (where $h\sim1800m$ is the maximum height of the orography) suggesting that the flow is likely to be blocked at low-levels, while the Rossby number $Ro=U/Wf=2.5$ (where $W\sim40km$ is the width of the orography in the east-west direction in Fig. 1) suggests that rotational effects are likely to be significant but not the dominant factor in determining the flow.

The orography data is taken from the GLOBE dataset and has a grid-spacing of approximately 1km. This data was smoothed using a Raymond filter so that features with length-scales of 10km were damped by 50%. The major axis of the smoothed orography was found using the technique described in Lott and Miller (1997). The island was then rotated about this axis in a domain with a fixed westerly wind in order to represent different incident wind directions.

3. FLOW FEATURES

Fig. 2 shows snapshots of the horizontal wind at 50m above sea level for six simulations with different incident wind directions. In Fig. 2 (a) the upstream wind is perpendicular to the major axis of the orography. On the upstream (left) side of the island there is a region of blocked flow (here the term blocked flow refers to a situation where the low-level flow has been reversed). Further upstream there is a much larger region of deceleration. This deceleration leads to geostrophic imbalance with the unbalanced component of the Coriolis force accelerating the flow northward, forming a barrier jet parallel to the island which wraps around the northern tip of the island. Downstream there are two regions of strong down-slope winds ($>20ms^{-1}$) partly due to channeling of the wind between the two highest peaks (see Fig. 1). These strong down-slope winds occur regardless of the lower boundary condition (although the wind speeds near the surface are reduced when a no-slip lower boundary condition is used). Finally, in the wake vortex shedding occurs, perhaps in part excited by the strong down-slope winds.

It is interesting to compare Fig. 2(a) with Fig. 2(b) where the orography has been rotated by 180°. If the orography were symmetrical about both the major and minor axes (like the idealized Greenland modelled by Petersen et al. (2003)) then the simulations would be identical. However, the flow fields are clearly different, although both flows display the same bulk features (upstream blocking, barrier jet, strong down-slope winds, vortex shedding). The region of blocking has moved southwards in Fig. 2(b), since the highest peaks are now near the southern end of the island, and the jet now escapes over the low (northern) end of the island instead of wrapping around it. The strong down-slope winds are in similar locations relative to the orography however the region of strong winds associated with the lower end of the island is larger in Fig. 2(b) as these winds are now also fed by the jet escaping over the island.

The flow fields in Fig. 2(c) and (d), where the flow is parallel to the major axis of the orography, are very different to those in Fig. 2(a) and (b). There is much less disturbance to the upstream flow since the mountain is now more streamlined. Both simulations have regions of decelerated flow to the south of the island and accelerated flow to the north. The down-slope winds are much weaker than in Fig. 2(a) and (b) and the wake regions are smaller, with the vortices remaining attached to the island for the duration of the simulation. However the flows in Fig. 2(c) and (d) also differ significantly from each other. In Fig. 2(c) the high mountains are located near the western end of the island and thus the region of deceleration is located near the western end of the island with flow escaping to the north forming a jet. In contrast the decelerated region lies further downstream in Fig. 2(d) and the jet is now driven by deceleration of the flow near the mid-point of the island and fed by down-slope winds through the gap between the two highest mountains.

Fig. 2(e) and (f) show the flow fields when the incident wind is oriented at an angle of 30° to the major axis of the orography. The upstream flow in these simulations is more effectively blocked than in Figs. 2(a) and (b) since the orientation of the island is forcing the air southwards and is thus opposing the northward acceleration of the flow due to the unbalanced component of the Coriolis force. Again, although the same bulk features are present in Fig. 2(e) and (f) the details are different.

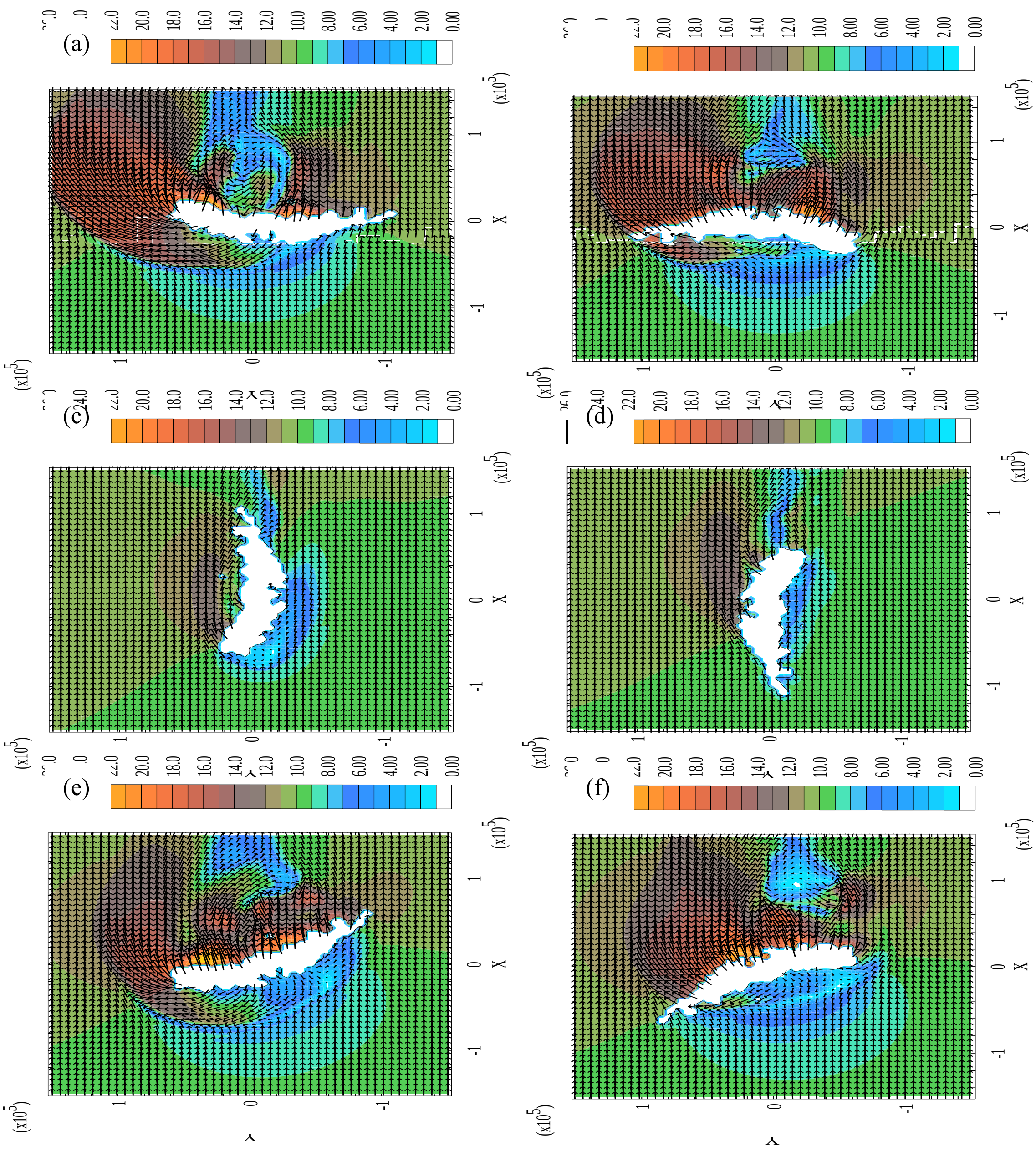

Figure 2: Horizontal wind vectors plotted at 50m above sea level. The coloured contours represent the horizontal wind speed at that height (in ms^{-1}). The incident wind is from left to right with the orography rotated by (a) 0° (b)180° (c)+90° (d)-90° (e)+30° and (f)-120°. The scales on the X and Y axes are in units of 10^5m. Note that these plots do not show the full domain.

In summary, it is clear from Fig. 2 that the flow fields are sensitive to the upstream wind direction. In contrast to an idealized symmetrical mountain the flows are also sensitive to a 180° rotation of the orography. Since none of the SSO drag parametrizations currently distinguish between opposite wind directions the drag in these simulations is of considerable interest and is discussed in Sec. 4.

4. DRAG

Fig. 3 shows the area average pressure force resolved in the direction perpendicular to the major axis of the orography plotted against the angle between this direction and the upstream wind. Concentrating first on our modelled results (black stars) it is clear that the variation of drag with wind direction is approximately sinusoidal. This sinusoidal variation occurs because the cross-ridge component of the wind varies when the wind direction is altered (for constant upstream wind speed). For orography that is symmetrical about the centre-plane (e.g. the results of Petersen et al. (2003)) we would expect the variation to be perfectly sinusoidal. The fact that our results are so close to a sinusoidal shape suggests that the asymmetry of our real orography only has a small impact on the pressure force. Surprisingly the magnitude of the pressure force differs by less than 10% when the orography is rotated by 180° from any initial orientation (e.g. +30° and -150°), despite the differences in the flow fields highlighted in Sec. 3.

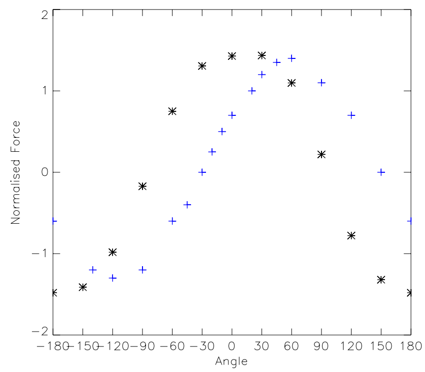

Figure 3: The pressure forces resolved in the direction perpendicular to the major axis of the orography plotted

Careful inspection of Fig. 3 reveals that the maximum normalized pressure force occurs when the upstream wind direction is about +20°. This shift is caused by rotational effects since (as discussed in Sec. 3) the low-level flow is more effectively blocked when the incident flow is at a slight angle to the major axis of the orography. The Petersen et al. (2003) simulations (blue crosses) show a larger shift in the peak pressure force since they have a much smaller Rossby number (Ro~0.4) than our simulations.

5. CONCLUSION

Our simulations have shown that the flow fields are sensitive to the incident wind direction, with even simulations with the orography rotated by 180° from any initial orientation exhibiting considerably different flow fields to those observed for the initial orientation. However, the variation of the across-ridge pressure force is approximately sinusoidal with the magnitude of the surface pressure force varying by less than 10% between simulations with the orography rotated by 180° from any initial orientation, suggesting that the pressure force is insensitive to the asymmetry of the orography. This lack of sensitivity to the asymmetry of the orography is encouraging for NWP since SSO drag parametrizations do not distinguish between these cases. However, the results presented here may be specific to South Georgia and thus future work will investigate flows past different real orography to assess the robustness of the results presented here.

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