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WIND FORECAST AROUND THE ANDES USING THE SLOPING DISCRETIZATION OF THE ETA COORDINATE

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1. Introduction

The Andes Cordillera is a major feature of the South America which plays an important role in the circulation on this continent. Low level jets and downslope winds are frequently observed along the eastern slopes of these mountains, in particular around 35° S and 15° S. Organized deep convection tends to form at the exit regions of these winds, and jets in the evening. Simulation and reanalysis data have shown that model outputs tend to underestimate the strength of these winds. Consequently, organized convection is also delayed or missed in the model simulations.

Most models use terrain following sigma coordinate. Above steep mountains large errors then can be produced in the calculation of horizontal pressure gradient force as the vertical coordinate surfaces also become steep. The step-mountain eta coordinate was designed to reduce these errors as its surfaces are quasi-horizontal. Overall, very eta-favorable results followed in comparison with various sigma coordinate results; yet, a problem was identified in the late nineties in simulating intense downslope winds using the step-mountain eta discretization. To address this problem a refined eta coordinate discretization was developed, so as to allow slantwise transports through half-open vertical sides of steps at places where the geometry of mountains makes this desirable.

The objective of the present research is to evaluate the impact of this sloping steps eta discretization in two major wind related phenomena near the Andes, South American low-level jet (LLJ), and the downslope zonda wind that occurs in the lee of the Andes.

2. Methodology

a. The Eta model as configured

The Eta Model was configured with 15 km horizontal resolution to cover a domain approximately between about 41° W and 77° W, and 38° S and Equator, which includes the steepest slopes of the Andes. The model is using rotated spherical coordinates so that when centered off the Equator – the center we used was at 19.5° S and 59.5° W – its lateral boundaries are not lines of constant latitudes and longitudes; a part of the model domain included within such lines is shown in Fig. 1. Our LLJ case we have run with both the 38 and 50 layer vertical resolution; 50 layer resolution was retained for the zonda case. The increase in the number of layers results of course in more realistic representation of topography, and also in more frequent fluxes through the half-open sides of steps. Control runs for each of our two cases were compared with the runs using the new sloping steps eta discretization.

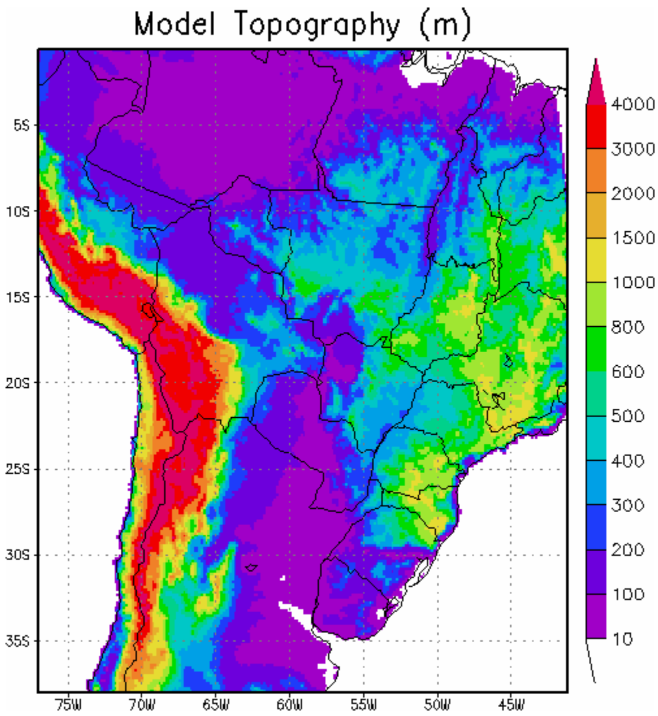

Fig. 1. The model domain and topography used for the experiments reported upon.

Recall that in the Eta convection is generated by a modified Betts-Miller scheme (Betts and Miller 1986), while microphysics of the large scale precipitation is handled by the Ferrier scheme (Ferrier et al. 2002). The land-surface processes are parameterized by the Noah scheme (Chen et al. 1997). The radiation package was developed by GFDL.

The lateral boundaries in our experiments were updated every 6 hours from the CPTEC T126L28 global model forecasts, to run the operational CPTEC Eta 40 km/38 layer model, on its operational domain, considerably larger than the domain of Fig. 1. The Eta 40 km/38 layer model in turn supplied boundary conditions for our experiments on the domain shown above. Initial conditions for both cases were obtained from the T126L28 global model. Our experiments used the initial monthly climatology of soil moisture and seasonal albedo derived from the same CPTEC global model.

b. Overview of the sloping steps eta discretization

Very early in the modern era of the primitive equation modeling it was understood that the possibility of large errors in the calculation of the pressure gradient force (PGF) when using terrain-following (sigma) coordinates is a problem that needs attention. The earliest attempt of addressing the problem was that of the vertical interpolation from sigma back to constant pressure surfaces (Kurihara 1968). This of course is not attractive for obvious reasons and no wonder it is not used. Numerous subsequent methods of addressing the problem have been proposed; the review paper of Mesinger and Janjic (1985) summarizes 5-6 of those. More methods have been proposed since, e.g., the one by Lin (1997). It was pointed out by Mesinger (2004a) that none of these avoid the possibility of large errors at places and at times as there is a limit to the validity of approximations to pressure gradient force when using the sigma system, this limit being exceeded for slopes of sigma surfaces beyond a threshold value. As the horizontal resolution is increased, this threshold limit is reduced if the horizontal resolution of topography and thus its realism is increased as well, which of course is a normal thing to do.

Even so, the move toward quasi-horizontal coordinates, such as the eta proposed by Mesinger (1984), avoiding the problem at no loss in the simplicity of schemes, was far from universal. Thus, plans at NCEP at present foresee even a switch from the Eta to the so-called Nonhydrostatic Mesoscale Model (NMM), derived from the Eta, but changed to use the sigma coordinate (Janjic 2003). The main motivation for this is the poor result a 10-km Eta achieved on a 1997 case of the so-called Wasatch windstorm, while the sigma system MM5 did well (McDonald et al. 1998); with this followed by arguments of Gallus and Klemp (2000). Quite a widespread interpretation as a result was that the eta coordinate is "ill suited for high resolution prediction models". For example, Mesinger and Jovic (2004) display a list of five references containing this or similar statements.

A simple explanation of the Eta model's downslope windstorm problem was however offered by Mesinger and Jovic (2004), that has nothing to do with resolution. It is only that the event which resulted in the problem having a visible impact, a downslope windstorm, is an event that for its simulation requires high resolution. The problem, as suggested, is not due to the eta coordinate, but is due to the simple step-topography discretization in use in various Eta model versions since the Mesinger et al. (1988) paper. More refined discretizations are possible; one, allowing for slopes on parts of the upper sides of topography boxes, was developed and tested by Mesinger and Jovic (2004). The Mesinger and Jovic scheme is particularly attractive for its simplicity of implementation, as code-wise it is an add-on to the existing step-topography Eta codes. Thus, it is in use in a number of places, including the operational Eta models run at CPTEC and at a private company SEWA, Belgrade.

It is worth pointing out however that even the step-topography operational Eta at NCEP continues enjoying significantly better precipitation scores than the sigma system NMM, and also the NCEP's Global Forecasting System (GFS), over the western United States' area of complex topography. Note, for example, precipitation scores displayed in Mesinger and Brill (2004), and in Mesinger (2006). It does that in spite of its considerable handicap in using an underperforming data assimilation system (e.g., Mesinger 2004b, slide 44).

On the other hand, there is a number of other highly respected model developers or groups who in their recent work have chosen to use or develop an option to use a quasi-horizontal eta or eta-like coordinate. These are the developers of the University of Wisconsin model (Tripoli 2006), the Colorado State University RAMS model (R. Walko, personal communication), the German Weather Service's Lokal Modell (Steppeler et al. 2005) and the MIT ocean-atmosphere model (Marshall et al. 2004). A very recent addition to this list is the high-visibility NASA/Goddard climate modeling group led by Jim Hansen, which has redesigned its model to use an eta-like coordinate, with highly encouraging results (Gary Russell, 2006, personal communication).

Note that the eta coordinate (Mesinger 1984, also in Mesinger et al. 1988) is defined by an equation, relating eta to pressure and surface pressure. The steps are only the simplest discretization of topography using the coordinate. In Fig. 2 a schematic is presented of a 2D section of an eta grid, with step-mountain discretization, to be used following Mesinger and Jovic (2004) for a suggestion as to what goes on to lead to the Eta downslope windstorm problems as encountered.

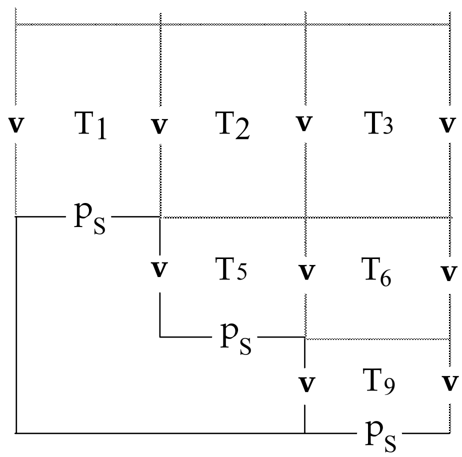

Fig. 2. Schematic used for suggestion of an explanation of the Eta step-mountain discretization problem.

Suppose that in Fig. 2 we are looking at a section of the lee slope with the air flow that ought to be downward along the slope according to the continuous equations. Note that with the step-mountain discretization what is imposed on the flow are eta vertical velocities of zero at the p_S points, and horizontal velocities of zero at the $\mathbf{v}$ points at the sides of steps. The discretized flow is not aware of “step corners”, that seemed to have been blamed for the flow separation by Gallus and Klemp (2000); on the other hand, the boundary conditions at the sides of steps above could be interpreted as implying the corners.

In analyzing the situation let us refer to grid boxes above by the indices of the T points. From the box 1 the flow enters box 2 to the right of it. Being conditioned, as assumed, stratification-wise to move downward, the flow will move downward by way of the eta vertical velocity at the interface between the boxes 2 and 5. But some of the air that entered box 2 will move horizontally into box 3.

What is missing in this course of events is the flow directly from box 1 into 5, which would have existed had the discretization accounted for the terrain slope between boxes 1 and 5. As a result, not all of the air which should have moved slantwise from box 1 directly into box 5 gets to it, since some of it is erroneously deflected horizontally from box 2 to into box 3. This is suggested by Mesinger and Jovic as the step-mountain discretization problem which led to the tendency for the separation of the flow in downslope windstorm cases run with the Eta.

The obvious remedy is to allow for slopes by relaxing the boundary conditions referred to above. With the eta vertical velocity allowed at p_S points, the pressure tendency equation becomes (Mesinger 2000)

$$\frac{\partial p_S}{\partial t} = -\int_0^{\eta_S} \nabla \cdot \left(\mathbf{v} \frac{\partial p}{\partial \eta} \right) d\eta - \left(\dot{\eta} \frac{\partial p}{\partial \eta} \right)_S \qquad (1)$$

There are however various possibilities how to define slopes and implement discretization more refined than used in the NCEP operational step-topography Eta. The approach chosen by Mesinger and Jovic aims to maintain the Eta features of approximately equal grid box volumes in horizontal, since with Arakawa-type conservation schemes such as used in the Eta this is felt to result in a robust code from the CFL point of view, and is also beneficial by way of having flux-type schemes approximately become finite-volume schemes. Both of these are felt to be strong features of the step-topography Eta.

With this restriction, still various options are available. The option used by Mesinger and Jovic is that of defining topography slopes at the $\mathbf{v}$ points, the highest of those that are blocked in the step-mountain discretization. With this approach, slopes are defined if one of the four surrounding h points is the highest of the four and thus responsible for blocking with the present discretization, and if two nearest neighbor h points are the highest. Otherwise, the slope is set to remain zero. Slopes are considered discrete, so as to be valid between neighboring h boxes, along half of their horizontal sides, and also along half of their vertical sides. Thus, in the schematic of Fig. 2, for the discretization of (1) and other relevant equations or terms, the step topography is considered replaced by straight lines connecting the two pairs of neighboring p_S points. Slantwise mass divergence contributions are evaluated and incorporated in the calculation of the first term on the right side of (1). Note that this scheme does not require specification of the eta vertical velocity in (1), as slantwise mass transports in fact account for the second term on its right side. Also other schemes are modified or added, to allow for slantwise advection of various quantities consistent with the advection of mass.

An example of the resulting sloping steps vertical grid is shown in Fig. 3. The **v** box immediately above the slope exchanges momentum with **v** boxes of two layers at its right side, with half of what used to be the vertical side of the step at lower left of the schematic now considered open. At the same time, there is a direct slantwise temperature exchange between temperature boxes denoted by T_1 and T_4 in the figure.

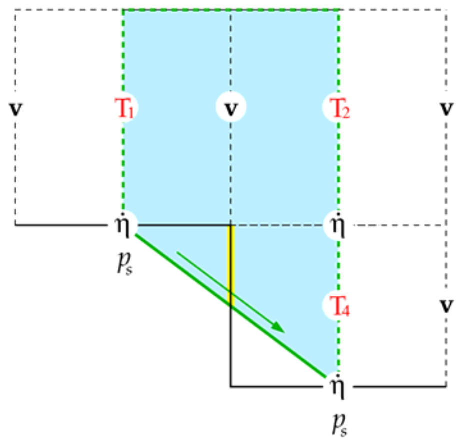

Fig. 3. Schematic of the vertical grid of the sloping steps eta discretization used. Slantwise momentum and temperature transport occurs along half of what used to be vertical side of the left lower box with the step-topography eta discretization.

The result of Mesinger and Jovic's emulation of the Gallus-Klemp experiment is shown in Fig. 4. Its left panel shows a reproduction of their Fig. 6(a). This result is obtained using a full 3D Eta code, dynamics only, running a square domain, with variables prescribed not to change along one of its diagonals. Flow separation in the lee as seen in this panel was considered by Gallus and Klemp illustration of the Eta downslope windstorm problem; just as in their plot, a velocity of only between 1 and 2 m/s is seen the left panel plot immediately behind the obstacle next to the ground. In the right panel, obtained using the outlined sloping steps discretization, a considerably greater velocity is seen in the lee next to the ground, of between 4 and 5 m/s.

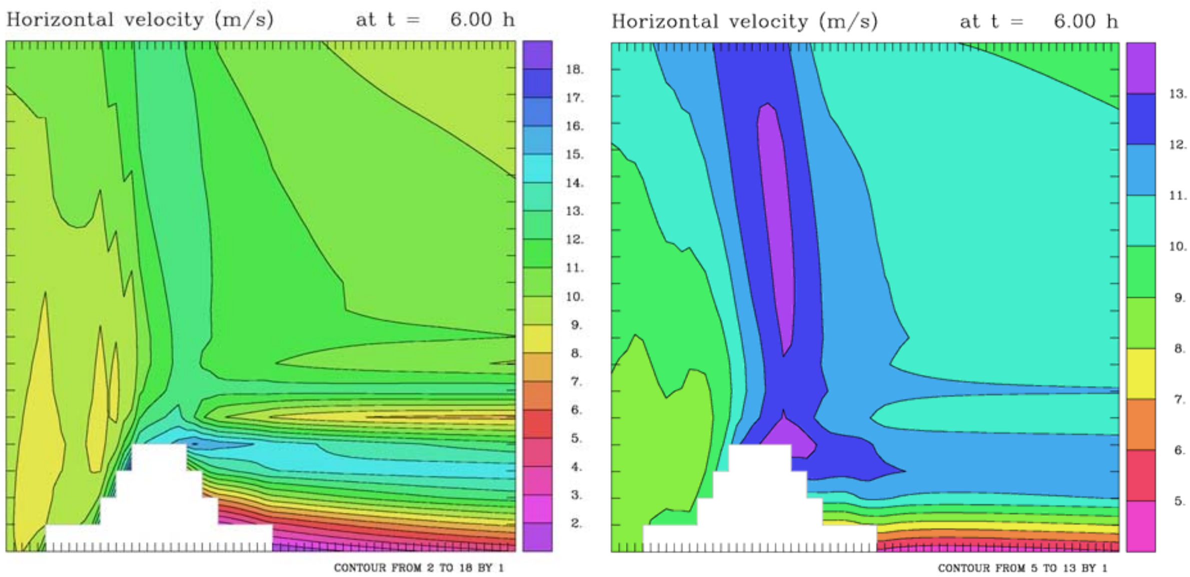

Fig. 4. Gallus-Klemp experiment, with parameters chosen so as to mimic the result shown in Gallus-Klemp (2000) Fig. 6(a). Control, left panel; code modified so as to use sloping steps eta discretization, right panel.

The version of the model used here, having an option to use the sloping steps discretization, is available at http://www.cptec.inpe.br/etaweb.

3. The South American real data experiments

a. The low-level jet case

Needles to say, South American topography is particularly suitable for tests of the impact of the refined eta discretization. At the same time, for features not directly related to the downslope wind problem described above one might not expect a spectacular difference in results, given that the performance of the Eta using step-topography discretization is as successful as summarized above.

The LLJ in the case we ran reached its maximum intensity on 18 January 2003. It is one of the cases included in the South American Low-Level Jet Experiment (Vera et al. 2006). As stated, for this case we have done experiments using two vertical resolutions; 38 and 50 layers. We here show results obtained using the 50 layer resolution. Experiment done with the 38 layers resolution showed less of an impact.

In Fig. 5 we show profiles at 31° S obtained at the 45 h forecast time, valid at 0900 UTC 17 January 2003. The LLJ is seen to be located between about 65° W and 66° W as indicated by the strong northerly component of the meridional winds seen in the top left panel of the figure. Maximum values are exceeding 18 m/s. The difference between the sloping and the original eta discretization, the top right panel of Fig. 5, shows that as a result of the sloping discretization these northerly winds were generally somewhat strengthened above the valleys, and weakened above the tops of mountains.

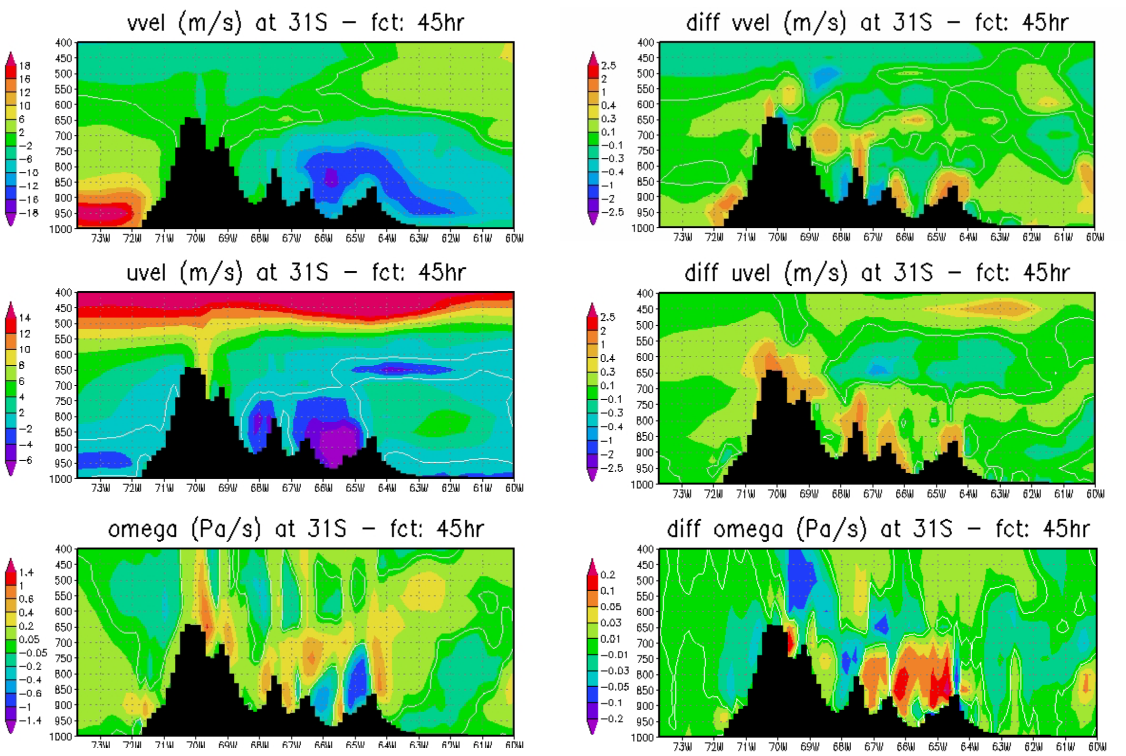

Fig 5. Meridional wind (m/s), zonal wind (m/s), and the omega vertical velocity (Pa/s) cross sections at 31° S, and at 45 h of our LLJ case forecast, left upper, middle, and lower panel, respectively, obtained using the sloping steps eta discretization. Same, but differences between the sloping steps and the traditional eta discretization, right panels.

To the east of the main barrier at 70° W, winds are seen to be downslope all the way to about 67° W. The intensity of downslope winds immediately in the lee of the main barrier increased due to the discretization change, as expected. The downward velocity along the steep slope just behind the main barrier increased by as much as about 20 percent. The difference in zonal winds shows that the intensity of westerly winds increased as well due to the discretization change, in particular over and around the tops of various barriers.

The difference patterns show values that might not be considered large, but at the same time are not negligible. The major changes occur on top and in the lee of topographic barriers. In an LLJ event, winds are predominantly along valleys, so the refined discretization was not expected to result in large wind field changes. Still, based on the existing understanding of the problem addressed, the impact shown can certainly be considered positive.

b. The zonda case

We have run our zonda case experiments using the same domain and lateral boundary/initial condition setup, but 72 hours ahead.

The zonda are strong warm and extremely dry winds that occur east of the Andes Cordillera. They are occasionally observed descending from mountains toward a valley or plain. Such winds have different names, depending on where they blow: “foehn” in central Europe (Germany, Austria, Switzerland) (Fleagle 1950; Klemp and Lilly 1975), “chinook” in Canada and the United States east of the Rocky Mountains (Brinkmann 1974; Zydek 2000), “Canterbury-nor’wester” in New Zealand (Lamb 1974), “berg wind” in South Africa (Lindesay 1990), and “zonda wind” in Argentina (Norte 1998), to the east of the Andes Cordillera near the Zonda Valley. These generally exhibit the so-called foehn effect, which is produced when the air descends adiabatically from the lower or middle troposphere to the foothills on the lee side of mountain ranges (Seibert 1990). Even though this process roughly describes the phenomenon, its spatial extension, intensity, frequency, and effects depend strongly on the local topographic characteristics and regional atmospheric circulation.

The Andes Cordillera runs meridionally from about 55^0 S to 10^0 N with a mean width of only 200-300 km. Its height varies with latitude. From the southernmost latitudes to 35^0 S, the mean Andes height does not exceed 2500 m, which allows westerly winds to pass over the mountains without too much blocking. North of 35^0 S, the Cordillera rises rapidly, achieving a mean altitude of 4500 m, with many peaks over 6000 m, such as the Aconcagua Peak (6959 m).

The zonda episode selected occurred between 1200 UTC 17 May and 0000 UTC 18 May 2005. It could be characterized as a strong surface episode. In Fig. 6 we display sections of surface synoptic plots with observations for this period, at 6 h intervals. The sections shown span latitudes from 30° S to 35° S, which is the area including several major peaks higher than 6700 m. A surface temperature increase from 2 to 27°C in 6 h, from 1200 UTC to 1800 UTC, can be seen recorded at the station San Juan, in the upper left section of the plots, with a similar increase at the station just to the south of it.

The initial condition we used for this case was one of 1200 UTC 15 May 2005. In Fig. 7 we show a sequence of cross sections at 33° S of the omega vertical velocities, valid at 57, 60 and 63 h, top, middle and the bottom left panels, respectively, of our forecast with step topography eta discretization. Note that the middle panel plot corresponds to the time of the right panel of Fig. 6. In the right panels of Fig 7 we show the differences between the sloping steps and our standard step-topography discretization forecast, valid at the same times.

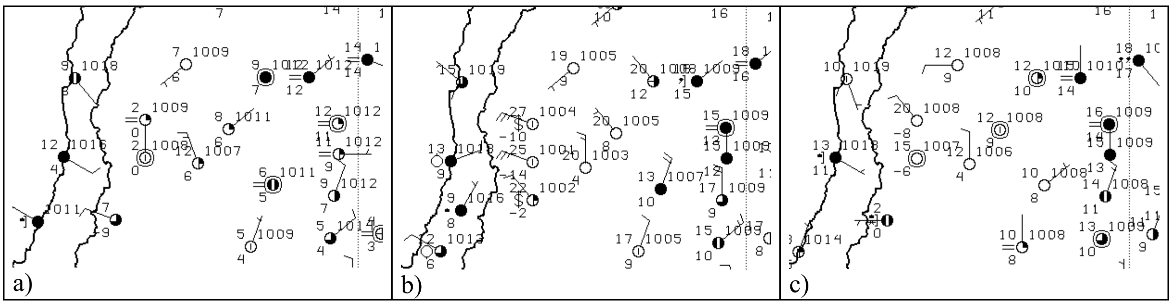

Fig. 6. Synop station data for: a) 1200 UTC 17 May 2005; b) 1800 UTC 17 May 2005, and c) 0000 UTC 18 May 2005. The area displayed spans latitudes form about 30° S to 35° S.

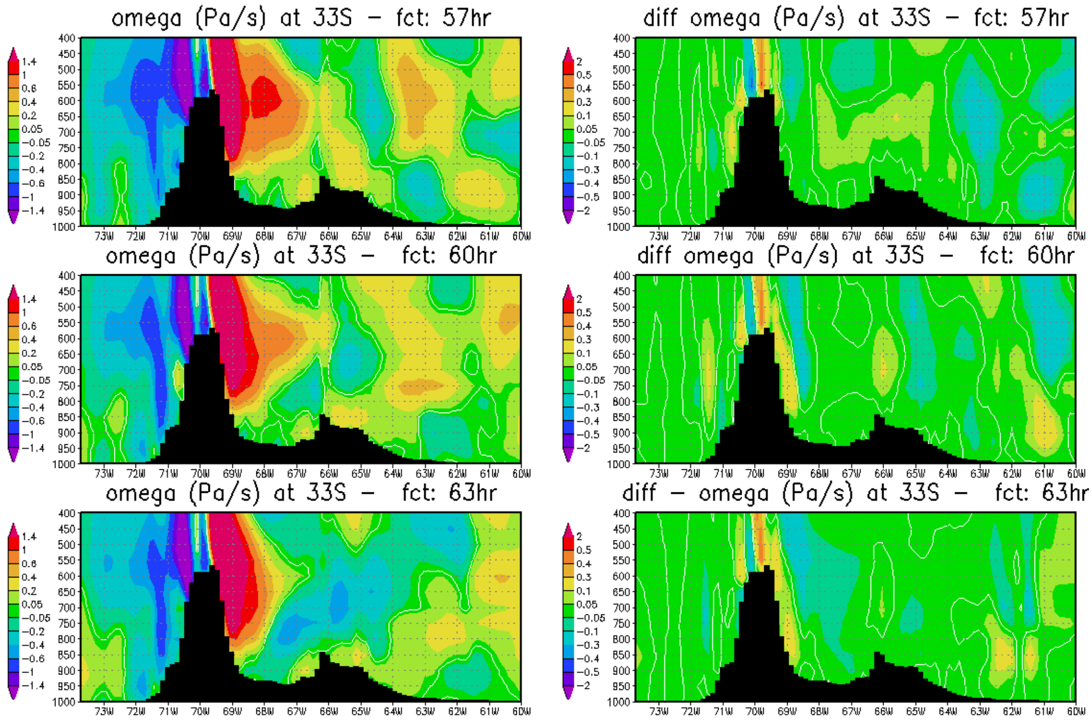

Fig. 7. Cross section of the omega vertical velocity (Pa/s) at 33° S, at 3 h intervals, of our zonda case forecast using step-topography eta discretization, left panels. Note that the 60 h forecast, middle left panel, is valid at 0000 UTC 18 May 2005, same as the right panel of Fig. 6. Differences in the omega vertical velocity between the sloping steps and the step-topography eta discretization forecasts, right panels.

A considerable increase in downward velocities in the lee of the main barrier is seen to have occurred as a result of the sloping steps discretization. Values above 0.1 Pa/s are seen along extended regions in the lee of the main barrier at 60 and 63 h forecast times, all the way to the foothills of the main Andes ridge. Once again, this is on the order of 20 percent and even more of the velocities without slopes at the foothills of the main barrier.

4. Conclusions

We have run tests on the performance of the recently developed sloping steps eta discretization in two cases of particular interest for the South American general circulation and high-impact local weather. The discretization developed aims to improve on the weakness of the step-topography eta discretization in apparently not performing well in forecasting some of the intense downslope windstorms. While our first case, one of the low-level jet, is not typical of intense downslope winds, it is still associated with a prominent downward motion along the lee slopes of the Andes. Our sloping steps discretization experiment resulted in considerably increased downward winds, which appears welcome.

While the performance of the standard Eta seems to have been quite satisfactory in zonda experiments done by Seluchi et al. (2003) already with the standard step-topography discretization, our sloping steps experiment on a major zonda wind case also led to a considerable increase in the intensity of downward winds. In view of the widespread image of the Eta not doing well downslope windstorms, this certainly is a result worthy of attention. But one should also recall the continued highly successful performance of the operational Eta at NCEP in forecasting high-impact heavy precipitation in the United States western regions of complex topography, as evidenced by precipitation scores of the Eta in comparison with NCEP's sigma system operational models, pointed out above.

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