Review: On the descent of Alpine south foehn (Jansing, Papritz and Sprenger)

Summary

The paper explores why foehn air descends in the lee of topographic obstacles through numerical simulations at the kilometer-scale of 15 south foehn events in the Swiss Alps. The paper is well structured, the writing is clear and the figures are well chosen. However, three fundamental issues exist. (1) The main conclusion that gravity waves trigger foehn descent rests upon a false premise, (2) an alternative hydraulic mechanism is mentioned but not explored, and (3) the numerical simulations are likely incapable of properly reproducing flow separation, which is crucial for how the flow descends. For these three reasons, the recommendation is to reject the paper. However, the paper could be a fruitful addition to the foehn literature once these three issues have been properly addressed.
The following explains the reasons for the rejection in more detail.

Reasons for rejection

Descent of air shapes gravity waves, not the other way around: The descent of the air behind topography makes it possible for large gravity waves to form, rather than gravity waves causing the descent as the paper argues. When air impinges on an obstacle in stably stratified air, a gravity wave will be launched. Its shape and amplitude, however, will not only depend on the non-dimensional height of the obstacle (the product of relative height above incoming isentrope, stability and the inverse of speed), which is a function of the *upstream flow only*, but also on the shape of the obstacle *including its lee side*.

Downstream descent is limited by real or virtual topography. Virtual topography is formed by the level of neutral buoyancy of the overflowing air with respect to the pre-existing air on the downwind side. Descent is only possible when the level of neutral buoyancy of the overflowing air in the downstream air is lower than the upstream altitude of the air, i.e. when the potential temperature of the upstream air is lower than the pre-existing downstream air at the same altitude. Armi & Mayr (2015) showed this in detail with observations from instrumented aircraft (in-situ and cloud radar), dropsondes, radiosondes and satellite data.

The present paper even acknowledges the fact that gravity waves depend on how far air can descend (and not vice versa) in lines 568-569 of the conclusions by stating that “nocturnal cooling and the resulting formation of a cold-air pool impede strong descent of foehn air by effectively attenuating the mountain waves” without concluding that the descent cannot go further than to where this isentrope is located on the downstream side.
The third row of Fig. 10 (09 UTC 28 Feb) shows minimal gravity wave activity because the underlying virtual topography produced by nocturnal cooling is so smooth. The previous and the subsequent afternoons (13 UTC) of rows 1 and 4, respectively, have warmer leeward temperatures caused by daytime warming mainly by sensible heat fluxes (and initially by the turbulent erosion of the cold pool). Consequently gravity waves are larger.

Alternative descent mechanism ignored: In the introduction the paper describes two main mechanisms that have been proposed in the literature to explain the descent - gravity waves and hydraulics - differential density (colder air upstream descending to its level of neutral buoyancy downstream). The claim in lines 75 - 77 that the hydraulic approach is applicable to shallow but not deep foehn is not correct (e.g. Armi & Mayr, 2007; Armi & Mayr, 2015; Winters & Armi, 2014).

The present paper only explores the gravity wave mechanism and ignores the hydraulic one despite the rich material available from the numerical simulations. The discussion subsection 5.2 ("What other factors influence the descent?") does not even mention the second mechanism anymore! This is a pity because the study has ample data to test both mechanisms whether they are the reasons for the descent and thus provide more material to further the discussion in the foehn community. The testable characteristic for the hydraulic response is that substantial descent starts when the overflowing air becomes colder (in terms of potential temperature) *relative* to the downstream air at altitudes below which it descends. Similarly, there need to be testable characteristics for the gravity wave mechanism that avoid, for example, the speculative attribution of the "intermittent periods of weak vertical motion" (lines 450-451) in the April 2018 case study to the "variability of wave-induced subsidence". With the alternative explanation this could be directly tested by examining whether the upstream air had become colder relative to the downstream one.
However, the most important aspect to test for the adequacy of the mechanisms is the evolution of the onset of subsidence in the simulations.

Questionable whether numerical simulations correctly reproduce processes that lead to downstream descent: COSMO, the numerical model used for the simulations, has terrain-following coordinates near the surface. The simulation setup also uses horizontal diffusion (lines 179-181). If the numerical diffusion acts along model surfaces, which are slanted in complex terrain, artificial vertical, cross-isentropic mixing will ensue since in general the terrain-following coordinates cross isentropes in a stably stratified atmosphere. As a result, air will not separate from steep downward sloping topography as in reality, but rather descend. There are no figures in the paper to substantiate this claim. However, this inference is supported by the fact that the strongest descent in the model *simulations* occurs along the steepest slopes behind the tallest mountains (lines 313-315 and Fig. 4b) whereas in *reality* steeper slopes are likelier to lead to flow separation. Pressure perturbations from a gravity wave alone will not be strong enough to force the flow down by 1500 m in stable stratification.
Observations in the ocean (Knight Inlet; Farmer & Armi, 2001, and references therein) and in the atmosphere (Owens Valley during the T-REX campaign; Mayr & Armi, 2010 see Figs. 5 and 6; Armi & Mayr, 2011) confirm that flow separates along steep slopes before it later descends when small-scale mixing forms a wedge of nearly stagnant and neutrally stratified air (away from the terrain) that separates the descending flow from the flow aloft.
The detailed observations of the oceanic "foehn" flow into Knight inlet demonstrated the importance of correctly simulating the boundary layer separation. Numerical simulations with an atmospheric model (Afanasyev & Peltier, 2001) and an oceanic model (Cummins, 2000) erroneously produced a large overturning wave soon after the flow started flowing over the sill (the oceanic equivalent of a mountain crest) contrary to what the observations showed. Only when Cummins (2000) modified the topography to force boundary layer separation did the oceanic model correctly simulate the evolution of the flow. The authors will need to show that the model adequately handles flow separation; currently there are no figures in the paper that would allow one to do that. This can be done by first examining the time it takes for the descent along the slopes to become established. If this time is not (much) larger than 2π /

N then the simulation will be incorrect. Second, the evolution of the descent must be visually inspected for congruence with observations of the initial flow separation and the way the wedge of the nearly stagnant and neutrally stratified air is formed that isolates the descending air from the flow above.

References:

Afanasyev, Y. D. & Peltier, W. R., (2001): On breaking internal waves over the sill in Knight Inlet. *Proceedings of the Royal Society London. A.,* **457**, 2799–2825. https://doi.org/10.1098/rspa.2000.0735.

Armi, L. & Mayr, G.J. (2007). Continuously stratified flows across an Alpine crest with a pass: Shallow and deep föhn. *Quarterly Journal of the Royal Meteorological Society*. **133**, 459 - 477. https://doi.org/10.1002/qj.22.

Armi, L. & Mayr, G.J. (2011): The Descending Stratified Flow and Internal Hydraulic Jump in the Lee of the Sierras. *Journal of Applied Meteorology and Climatology*, **50**, 1995–2011, https://doi.org/10.1175/JAMC-D-10-05005.1.

Armi, L. & Mayr, G. J. (2015): Virtual and Real Topography for Flows across Mountain Ranges. *Journal of Applied Meteorology and Climatology*, **54**, 723–731, https://doi.org/10.1175/JAMC-D-14-0231.1.

Cummins, P. F. (2000): Stratified flow over topography: time-dependent comparisons between model solutions and observations. *Dynamics of atmospheres and oceans*, **33**, 43-72. https://doi.org/10.1016/S0377-0265(00)00044-0

Farmer, D.M. & Armi, L. (2001): Stratified flow over topography: models versus observations *Proceedings of the Royal Society London. A.,* **457**, 2827–2830, https://doi.org/10.1098/rspa.2001.0802

Winters, K., & Armi, L. (2014): Topographic control of stratified flows: Upstream jets, blocking and isolating layers. *Journal of Fluid Mechanics, **753***, 80-103. https://doi.org/10.1017/jfm.2014.363