Slide 1: My assignment today was to talk about the effects of moisture on stable orographic flow. This is sort of an experiment – being the first one here, so I don't know what you know. You can give feedback to Heather later on as to whether or not it's at the right level. I did ask Heather to have you all take a look at the COMET module. I thought they did a very good job of explaining the fundamentals of how dry flow is modified by the presence of a mountain. So I'd like to take you from the ground up and give you more of a mathematical treatment to explore some of the issues particularly with the Froude number because that's what Heather originally assigned me to talk about. But I resist that because it's used in many different ways, some of which are not relevant to the flow. Let me show you my personal view, then, of how to think about this flow.

Slide 2: Starting at the beginning: Think about flow over a hill. This could equally well be flow over an air foil. The flow at upstream infinity, u-infinity, is equal to big U coming in from the left and going to the right. In our coordinate system, in x and z, the hill is specified by a height, h, and a wdith, a. The flow modification due to the presence of the hill has to be a function of the aspect ratio (h/a).

Slide 3: Life becomes more interesting when the flow is stratified. By stratified flow, I mean that the potential temperature, or in this case the virtual potential temperature, is a linear function of height. I show that in the upper-righthand corner. N squared is the Brunt-Vaisala frequency and is the vertical gradient of the virtual potential temperature. With this kind of simple atmosphere, the effects of the stratification are represented by this one parameter, N. If you do a dimesional analysis – look down at the bottom of the screen – in addition to the aspect ratio, there's another parameter, which is nondimensional. N has the units of 1 over time, h of course is length, and U is length over time. So this non-dimensional number is another number that will determine the orographic flow modification over the hill. Just a historical footnote, Nh/U, or U/Nh, both have been called the Froude number in the literature. I will stay with the Nh/U definition simply because it's easier to think about N becoming smaller in the numerator rather than N being in the denominator. So, Nh/U is sometimes called the nondimensional mountain height where h is the height of the mountain and it's nondimensionalized by the length scale, U, divided by N. We'll return to this model, because it's the basic model that people think about when you think about the effects of stratified flow over a mountain.

Slide 4: But there are a few complications you should be aware of. For example, if the flow has a lid like, say the tropopause, at a height big H, then that introduces yet another parameter into the problem. So if I add to my list of parameters that affect the flow, you could add in N big H over U. Or, since this is dimensional analysis, I could have added big H over little h. But in one way or another, big H affects the amount of flow modification over the hill. That's something to keep in mind.

Slide 5: Another popular model for flow over hills in the atmosphere is one where the potential temperature has a sudden jump or sharp increase, at a certain height, d, in this formulation. In this case, if you look over to the left, there's a flow coming in at relatively constant potential temperature capped by increasing potential temperature over a very narrow height interval, and then constant above that. So all the density stratification is confined to a very narrow layer. In this case, you may say, "What happens to N?" In this case, N basically becomes infinitely large over a small layer. So the only parameter that enters in is the integral of N over the layer. That integral of N is simply the difference in temperature. That then enters in as a reduced gravity in the problem. So, here's the g, the change in theta, divided by some normalizing constant (see lower right equation). This becomes the reduced gravity that is used in this nondimensional number which is the square-root of g prime d divided by U. Now, in this case here – this is the Froude number that William Froude knew back in the 19th century. In U over sqaured-root of g prime d, U is the velocity of that layer and g prime d – those of you that are familiar with shallow water theory will recognize this as the speed of the long wave on this layer. So the Froude number in the classic literature meant the velocity divided by speed of the horizontal wave that propagates on this layer. Now, in reality, in meteorological practice the flows are functions of height U-infinity is a function of height and theta-v is a function of height. And so, in reality there's a number of parameters that come into play in trying to understand the orographic flow modification. So, in reality, you should turn to a model to come up with the answer. But, these simple idealizations help you to understand what might be going on in various situations you might encounter.

Slide 6: Going back to the simplest model – the one with just a constant stratification – and without a lid and without an inversion. The simplest thinking on this with regards to precipitation is on what happens on the wideward side of the mountain. The perturbation velocity, u, is divided by the upstream velocity, big U.

Slide 7: In the case of weak stratification and/or a large incoming wind speed (shown in the top diagram), the maximum lifting will be along the windward side of the mountain. That's also where the maximum precipitation is going to fall. Whereas if you have a blocked layer, the upward motion will be, in a sense divorced from the slope of the mountain.

Slide 8: So, I'd like to talk a little bit about the effects of moisture. The first thing to do is to make sure we understand the concept of buoyancy and stratification. Here we have an element, or parcel. Going back to Archimedes – basically the gravity and it's the density of the parcel minus the density of the ambient environment divided by the density of the parcel. If the density of the parcel is greater than the density of the environment – then there's negative buoyancy and a downward acceleration. Substituting the potential temperature for density allows the relationship to be written this way (second equation). Then taking the environmental and imagining there's a small parcel displacement, you could re-crunch the environmental temperature as a Taylor-series expansion about the starting temperature and find the buoyancy is related to the vertical temperature gradient times the displacement. And, again, here's the definition of N-squared. This is for an unsaturated flow. As long as the flow is unsaturated, the vertical gradient of virtual potential temperature is not that different from the vertical gradient of theta. The buoyancy, then, is linearly related to and of opposite sign to the displacement.

Slide 9: This is why, for example, if you have flow over a mountain, it's a lot different than flow over an airfoil because flow in an airfoil is not stratified. For flow that's stratified is to say that a parcel going up and down it feels the effects of buoyancy and as it goes up, becomes colder than the environment. As it goes down it becomes warmer and so on and so forth.

Slide 10: When the flow is saturated, everything becomes very different – or potentially very different. For saturated flow, you have a much more complicated formula for the Brunt-Vaisala frequency. Without going into a lot of detail, it's basically that the latent heat release offsets the adiabatic cooling in the lifted parcel. So, in general you expect the saturated Brunt-Vaisala frequency to be less than the unsaturated.

Slide 11: This is illustrated in the simple diagram here. Suppose I have a parcel, given by the green parcel. Everything's the same in these cases except one parcel is saturated and the other is unsaturated. For the unsaturated parcel that gets lifted – you can see by the difference between the green dot and the black line, that it becomes a lot colder than the environment. Whereas a saturated parcel produces only a small buoyancy anomaly.

Slide 12: An extreme case you could think of is the case where the environment is exactly moist neutral. In this case, the lifted parcel has no difference in temperature from the environment and, therefore, no buoyancy. In this case, you have the saturated N equal to zero.

Slide 13: What do these things mean? For further reading on this topic, I suggest you see this article by Heather Reeves and myself. It was an exploration of the different microphysical effects on the Brunt-Vaisala frequency due to moisture, showing under what conditions you may or may not get blocking on the forward side of a hill. This, of course, again is relative to stable orographic precipitation.

Slide 14: I want to show you a few case studies where these effects came into play. This is a pre-case study for the MAP experiment. MAP, or Mesoscale Alpine Program, took place in 1999 on the Alps. On the south side of the Alps we're concerned with precipitation, on the north side with downslope winds and breaking gravity waves at high levels. Here was a case of the Piedmont flood of 1994. Those little yellow dots signify more than 300 mm in 24 h. The typical situation is warm moist air flowing in from the Mediterranean Sea up to the western Po Valley, and then up and over the Alps. These gray contours, this is the 1 km line, this is the 2 km-altitude line. As I'll show you in a moment, the air has no trouble going sea level to over 2 and 3 km in a very short distance.

Slide 15: A case study of this was done in Doswell et al in 1998 - MWR showing that the Milano sounding (back then it was Milan) was nearly saturated and moist neutral. Numerical simulations by Andreas Buzzi et al in 1998 (also MWR) show in a control simulation that the flow from the Mediterranean Sea up over the Alps had no problems going over and releasing latent heat and dropping rain. But, all, presumably under the condition of moist neutrality. A very interesting experiment that they performed was to simply turn off the effects of latent heating, which sets the latent heat release to zero. Therefore, no latent heat can be released. See the flow under the very same conditions – all this flow coming in from the south – gets deflected and it flows around and goes out through the gap between the western side of the Alps and the Massif Central in France.

Slide 16: The ability to flow around or flow over, again, depends on N-squared. The thing to remember then, that is if N-squared is small, the flow coming in from the south has no trouble going over, maybe in a single bound, the Alps. Whereas if N-squared is unsatured, then it (the flow) feels the full force of the Brunt-Vaisala frequency and then is deflected. In this case it's a leftward deflection because of the effects of Coriolis force.

Slide 17: Some interesting situations arise. You can have, for example, a moist tongue flowing in from the south, that is easily able to surmount the Alps. Whereas the flow farther to the east is unsaturated and experiences deflection. The place between where the airstreams meet is the place where the heaviest precipitation occurs.

Slide 18: You can see this in the control simulation from Buzzi et al. The flow over the Adriatic Sea, being unsaturated, was deflected into the Po Valley, whereas the flow coming over the south Mediterranean Sea made its way up and over the Alps.

Slide 19: Similar effects were found in other case studies. This (left panel) is from a study by Ralph et al of an atmospheric river. A number of drop sondes were analyzed showing moist neutral flow condtions, at least below 700 mb. This (middle panel) is the climatological distribution of annual precipitation in California showing several hotspots. Several studies have shown that this mechanism of flow over in the moist, neutral river part and airstreams coming from the south being deflected around the mountains produce convergence zones and areas of high precipitation.

Slide 20: Another interesting thing about the effects of moisture is that they can be asymmetric. If you have an atmosphere which is near saturated, or just at saturation, in a moist neutral environment, then an upward displacement would produce almost no buoyancy anomaly, but a downward displacement produces a big downward positive anomaly.

Slide 21: The example of this was in a simulation by Miglietta and Rotunno that we did a few years back – asking the question, "What happens there's exactly moist neutral flow impinging on a mountain?" In this case here, you can see in the cloud water field (lower right) showing the cloud water and rain coming out on the front side of the mountain. The buoyancy anomaly (top right) shows up with not a trace of anything [upstream of the terrain], but as the air emerges from the cloud on the lee side some of the standard effects of accelerated flow due to warming occur on the lee side of the mountain. This is reminiscent of the sorts of things that you see when you pull up descriptions of foehn winds – in that you have stable rain on the upwind side and the air emerges from the cloud as a dry foehn wind on the downslope side.

Slide 22: One final note of caution here, that Nh/U, this nondimensional mountain height, is only useful for N-squared being positive or zero. If N-squared is negative, then you have an unstable flow and small parcel displacements don't remain small - they keep going. So what you really need in these cases (N-squared less than zero) is a measure of total lifting – something like the Convective Available Potential Energy, which I show here in the formula. It's the measure of the buoyancy between the level of free convection and the level of neutral buoyancy.

Slide 23: Studies of this kind are very few. There's a few things that my colleague, Marcello Miglietta and I have been working on – looking at some ways of coming up with general considerations of the things to be taken into account when you're thinking about unstable flows over a mountain ridge. Some obvious things are the height of the ridge is such to lift the air to the level of free convection so that convection can be triggered. More subtle things have to do with the strength of the CAPE and the strength of the flow. For example, if you have very strong CAPE, this can produce a very strong cold pool that will flow away from the mountain. So, anyway, I think with this note of caution that these effects moisture on N-squared that are limited to the stable case. At this point, my presentation is finished and I'm ready for any comments or questions.