The Diabatic Pressure Difference: A New Diagnostic for the Analysis of Valley Winds

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ABSTRACT

The purpose of this article is to introduce a new diagnostic measure of the time-integrated diabatic (thermal) forcing of a valley–plain system. This measure can be used to synchronize the evolution of thermally induced valley winds with respect to their forcing. Differences among numerical models or model configurations originating from diabatic forcing versus those originating from the model dynamics (e.g., turbulence scheme, dynamical core, etc.) can then be distinguished.

1. Introduction

The evolution of the diurnal valley winds is the result of complex interactions between solar and thermal radiation, the land surface, turbulence, and the thermally induced flows themselves of various scales, from slope flows to plain-to-mountain circulations (e.g., Whiteman 2000; Weigel et al. 2006; Schmidli and Rotunno 2010). In a recent valley wind model intercomparison study, for example, Schmidli et al. (2011) find large differences in the evolution of the valley wind among nine mesoscale models, even for key aggregated quantities such as the along-valley wind averaged over the entire valley volume. For convenience, the evolution of the mean valley wind for a subset of the nine models is reproduced in Fig. 1. It was further found that there are quite large differences in the evolution of the surface sensible heat flux among the models. This leads to the question: are the differences in the simulated valley wind just the result of differences in the thermal forcing, or are there genuine differences among the models in their simulation of the valley wind?

Here we introduce a new diagnostic, the diabatic pressure difference, which can be used to synchronize the evolution of thermally induced flows among different models and different configurations of the same model. As a measure of the thermal forcing history of the valley wind system, the new diagnostic allows us to distinguish between differences originating from diabatic forcing (surface sensible heat flux, radiation flux divergence) to those originating from the model dynamics (e.g., dynamical core, turbulence scheme).

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2. The diabatic pressure difference

Here we define the diabatic pressure difference, a measure of the time-integrated diabatic (thermal) forcing of the valley–plain system. From the first law of thermodynamics, the volume-averaged density-weighted potential temperature change $\overline{\theta'}$ for an arbitrary control volume can be written as (Schmidli and Rotunno 2010)

$$\overline{\theta'} \equiv \frac{1}{M}\int_{t_0}^{t} dt' \int_V \rho \frac{\partial \theta}{\partial t} dV = \frac{AQ^n}{c_p M} = \frac{A(Q^d - Q^t)}{c_p M}, \qquad (1)$$

where M is the total mass of air in the control volume V; A is the area of the top surface of the control volume; Q^n and Q^d are the net and diabatic heat input into the control volume, respectively; Q^t denotes the heat loss of the control volume due to transport processes (due to advective and turbulent exchange of the control volume with its surrounding); and c_p refers to the heat capacity of the air. Note that the Qs are normalized by area A, and thus have units of J m^{-2}. During the daytime Q^d is approximately equal to the time-integrated surface sensible heat flux [i.e., $Q^d \approx \int_{t_0}^{t} H(t')\,dt'$]. During the nighttime, the diabatic forcing is composed of contributions from the surface sensible heat flux and the direct cooling of the atmosphere due to radiation flux

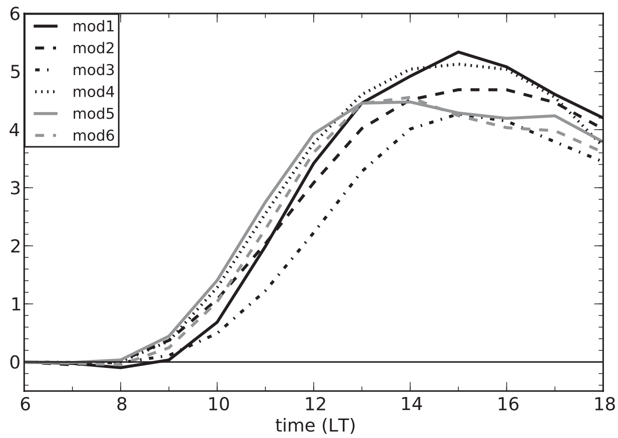

FIG. 1. Time series of the mean along-valley wind. The along-valley wind is averaged over the valley cross section and the first 20 km of the valley. The topography used in the intercomparison study consists of a valley with a horizontal floor enclosed by two isolated mountain ridges on a horizontal plain. The valley is 1.5 km deep, the ridge-to-ridge width is 20 km, and its half-length is 100 km. For further details see Schmidli et al. (2011).

divergence. Applying (1) to a control volume over the plain and to a valley control volume yields

$$\overline{\theta'_p} = \frac{Q_p^n}{c_p m_0} \quad \text{and} \quad \overline{\theta'_v} = \tau_v \frac{Q_v^n}{c_p m_0}, \tag{2}$$

where $m_0 \equiv M_p/A$ is the mass per unit area and $\tau_v \equiv M_p/M_v \approx V_p/V_v$. In deriving (2) we assume for simplicity that the two control volumes have the same horizontal extent (i.e., the same A).

As shown in Schmidli and Rotunno (2010), the valley–plain surface pressure difference between a valley point y_v and a point on the plain y_p, both on the valley axis, for a hydrostatic flow, is given by

$$\Delta p_{\text{sfc}} = -g m_0 \left(\frac{\overline{\theta'_v}}{\theta_0} - \frac{\overline{\theta'_p}}{\theta_0} \right) + \Delta p_{\text{top}}, \tag{3}$$

where Δp_{top} is the corresponding pressure difference at the height of the top surface of the control volumes and θ_0 is a reference potential temperature. Substituting (2) into (3) yields

$$\Delta p_{\text{sfc}} = -\frac{g}{c_p \theta_0} (\tau_v Q_v^n - Q_p^n) + \Delta p_{\text{top}}. \tag{4}$$

Equation (4) specifies the relation between the valley–plain surface pressure difference, the valley volume factor τ_v, the heat budget of the plain and the valley control volume, and the upper-level valley–plain pressure difference Δp_{top}.

Finally, we define the diabatic pressure difference as the valley–plain pressure difference resulting from the time-integrated diabatic forcing alone:

$$\Delta p^d \equiv -\frac{g}{c_p \theta_0} (\tau_v Q_v^d - Q_p^d). \tag{5}$$

The diabatic pressure difference, Δp^d, is a *measure of the time-integrated diabatic forcing*, primarily by the surface sensible heat flux, of the valley–plain system. Given the valley volume factor τ_v and an estimate of the temporal evolution of the surface heat flux $H(t)$, Δp^d can be calculated a priori, in contrast to Δp_{sfc} which depends on the advective and turbulent heat exchange of the control volumes with their surrounding and a possible upper-level contribution Δp_{top}. Introducing $\tau_q \equiv Q_v^d/Q_p^d$, the ratio of the normalized diabatic heat input into the valley to that into the plain volume, (5) can be expressed as

$$\Delta p^d = -\frac{g Q_p^d}{c_p \theta_0} (\tau_v \tau_q - 1). \tag{6}$$

It can be seen that Δp^d depends on three factors. First, the integrated diabatic forcing over the plain, which for daytime conditions is approximately equal to the integrated surface sensible heat flux over the plain. Second, the ratio of the plain-to-valley control volume τ_v, and third, the ratio of the valley-to-plain normalized diabatic forcing τ_q, which for daytime conditions is approximately equal to $\tau_q = H_v/H_p$, the ratio of the surface sensible heat fluxes.

It should be noted that Δp^d is a measure of the time-integrated *bulk diabatic* forcing of the valley–plain system and thus only indirectly related to the evolution of the along-valley wind. By design, it does not take into account the influence of the heat exchange between the valley and its surroundings or the influence of upper-level pressure gradients on the evolution of the valley wind, in contrast to Δp_{sfc}, nor does it take into account local gradients of temperature or pressure, which can be important in some situations (Schmidli and Rotunno 2010, 2012). It should be further added that as a measure of the thermal forcing history, it is not primarily the absolute value of the diabatic pressure difference, but the relative values of different cases that are of importance.

3. Application

As an example, we apply the concept of the diabatic pressure difference to a subset of models from the valley wind model intercomparison study of Schmidli et al. (2011). Time series of the diabatic pressure difference for the same models as in Fig. 1 are shown in Fig. 2. As the valley volume factor τ_v is identical for all models, the

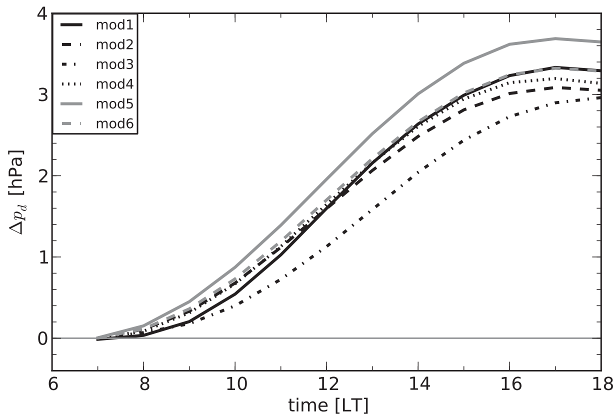

FIG. 2. Time series of the diabatic pressure difference, a measure of the integrated diabatic forcing of the valley–plain system. The dimension of the control volumes is 40 km in along-valley direction and 20 km in the cross-valley direction and 1.5 km from the surface to the top of the mountain ridges. The centers of the valley control volumes are located 30 km from the valley entrance on the valley axis. The diabatic pressure difference is calculated from hourly model output of the surface sensible heat flux used to estimate the diabatic heat input into the control volumes, Q_v^d and Q_p^d, and the application of (5).

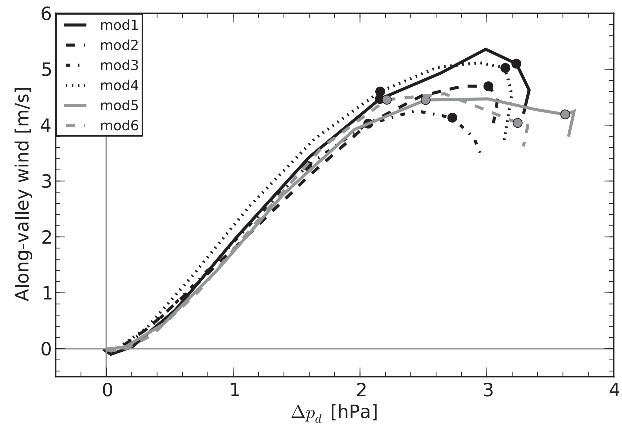

FIG. 3. Evolution of the mean along-valley wind (same average as in Fig. 1) as a function of the diabatic pressure difference. The filled circles indicate the state of the system at 1200 and 1500 LT.

differences in Δp^d are solely due to differences in the evolution of the surface sensible heat flux over the plain and in the valley (neglecting the very small contributions from the radiation flux divergence). It can be seen that these differences in the thermal forcing amount to temporal differences of up to 2 h. While the fastest model attains an integrated forcing of 2 hPa at 1200 LT, the slowest model attains the same forcing only at 1400 LT. There are also notable difference in the maximum magnitude of the forcing, ranging from 3.0 to 3.7 hPa.

Next we can use the diabatic pressure difference to synchronize the model simulations according to the integrated thermal forcing. Figure 3 shows the evolution of the mean valley wind as a function of the diabatic pressure difference Δp^d. It can be seen that for these six models the evolution of the mean valley wind, when corrected for differences in the thermal forcing, is very similar up to an integrated forcing of $\Delta p^d \approx 2$ hPa, which is reached, on average, at about 1200 LT. This implies that either only diabatic forcing is significant for the evolution of the mean valley wind, or that the other relevant processes, such as, for example, heat exchange with the valley surroundings and surface friction, are of almost identical magnitude in all six models (prior to 1200 LT). Further analysis shows that the latter is the case (Schmidli and Rotunno 2010, 2012). After about 1200 LT, as the cross-valley circulation and turbulence intensify, the differences among the models become larger. The intensification leads to larger differences in the heat exchange between the valley and its surroundings, which reduces the initially strong correlation between the evolution of Δp^d and the net forcing of the along-valley wind.

To conclude, Fig. 3 provides a concise summary of the evolution of two key quantities of the valley wind system, the integrated thermal forcing of the system, as measured by Δp^d, and its reaction to the forcing in terms of the mean valley wind.

4. Conclusions

In conclusion, the diabatic pressure difference is a concise measure of the thermal forcing history of the valley–plain system. As illustrated in the present note, it can be used to synchronize the evolution of thermally induced flows among different models and thus help to distinguish between differences orginating from the diabatic forcing to those originating from the model dynamics (e.g., dynamical core, turbulence scheme, and numerical smoothing). More generally, it can be used to account for one large source of differences between model simulations of thermally induced valley winds—be it different models or the same model with different configurations—namely, differences in the evolution of the diabatic (surface) forcing. Clearly this is useful, as often differences in surface properties (e.g., vegetation type and soil moisture) or in the land surface models are a (the) major source of uncertainty in the simulation of valley winds in idealized and real-case model setups (e.g., Chow et al. 2006; Schmidli et al. 2009, 2011). The application of the diabatic pressure difference is, however, not restricted to model intercomparison and sensitivity studies. As a measure of the thermal forcing history of the system, it can be used as a general tool for the analysis of thermally induced valley winds. It could, for example, also be used to analyze day-to-day or seasonal variability of the valley winds for particular locations.

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