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The role of a mid-air collision in drifting snow

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Abstract. Drifting snow, a common two-phase flow movement in high and cold areas, contributes greatly to the mass and energy balance of glacier and ice sheets and further affects the global climate system. Mid-air collisions occur frequently in high-concentration snow flows; however, this mechanism is rarely considered in current models of drifting snow. In this work, a three-dimensional model of drifting snow with consideration of inter-particle collisions is established; this model enables the investigation of the role of a mid-air collision mechanism in openly drifting snow. It is found that the particle collision frequency increases with the particle concentration and friction velocity, and the blown snow with a mid-air collision effect produces more realistic transport fluxes since inter-particle collision can enhance the particle activity under the same condition. However, the snow saltation mass flux basically shows a cubic dependency with friction velocity, which distinguishes it from the quadratic dependence of blown sand movement. Moreover, the snow saltation flux is found to be largely sensitive to the particle size distribution since the suspension snow may restrain the saltation movement. This research could improve our understanding of the role of the mid-air collision mechanism in natural drifting snow.

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1 Introduction

As one of the most important indicators of global climate change, snow cover is widely distributed over high latitude regions (Mann et al., 2000;Gordon and Taylor, 2009;Huang and Shi, 2017). Drifting snow is an important natural phenomenon in which air flow carries snow particles traveling near the surface, which not only profoundly changes the mass and energy balance of polar ice sheets (Déry and Yau, 2002;Gallée et al., 2013;Huang et al., 2016) but also may induce various natural disasters, such as avalanches, landslides and mudslides (Christen et al., 2010;Schweizer et al., 2003;Sovilla et al., 2006). In-depth studies of the laws of snow particle motion and various influencing factors are essential for understanding this complex phenomenon.

Numerical simulations have become one of the most effective ways of exploring the blown snow movement, and plenty of drifting snow models have been established since the end of last century. Generally, drifting snow models can be divided into Euler-Euler models (Bintanja, 2000;Déry and Yau, 1999;Lehning et al., 2008;Schneiderbauer and Prokop, 2011;Uematsu et al., 1991;Vionnet et al., 2013;Xiao et al., 2000) and Euler-Lagrange models (Huang et al., 2016;Huang and Shi, 2017;Huang and Wang, 2015, 2016;Nemoto and Nishimura, 2004;Zhang and Huang, 2008;Zwaaftink et al., 2014), in which snow particles are treated as one kind of continuous medium and individual particles, respectively. However, mid-air collisions, an important mechanism that influences the transportation of snow particles and the development of drifting snow, are hardly considered by current models. The Lagrange tracking model can capture the inter-particle collision process more explicitly and directly, and thus is more suitable for establishing the mid-air collision model.

In this work, a trajectory-based mid-air collision model for drifting snow is established on the basics of a three-dimensional drifting snow model in the turbulent boundary layer, and the effects of mid-air collision on the snow transportation and particle motion are mainly explored. This paper is structured as follows: Sect. 2 briefly introduces the model and method, Sect. 3 presents the model validation and simulation results, Sect. 4 discusses the results in detail, and Sect. 5 presents the conclusions.

2 Model and method

2.1 Turbulent boundary layer

The wind field is obtained from a large eddy simulation model of the Advanced Regional Prediction System (ARPS, version 5.3.3) (Xue et al., 2001). Considering the coupling effect between the snow particles and air flow, the fluid governing equations can be written as (Dupont et al., 2013;Vinkovic et al., 2006):

$$\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x_i}(\rho \overline{u}_i)=0 \tag{1}$$

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial \rho u_i u_j}{\partial x_j}=-\frac{\partial \tilde{p}^*}{\partial x_i}-\frac{\partial \tau_{ij}}{\partial x_j}+S_i \tag{2}$$

where ρ is the air density, t is time, x_i and u_i are the position coordinate and instantaneous wind velocity component, respectively, along three directions,

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$p^* = p' - \alpha\nabla(\rho\mathbf{u})$ includes the pressure perturbation and damping term (α is the damping coefficient), τ_{ij} is the sub-grid stress that is modeled by the Lagrangain dynamic closure model of Meneveau et al. (1996), and S_i is the source term that comes from the reaction force of the snow particles (Yamamoto et al., 2001):

$$S_i = -\frac{1}{\rho V_{grid}}\sum_{s=1}^{N_p} F_D \tag{3}$$

where V_{grid} and N_p are the volume and the number of particles in the grid cell, respectively. $F_D = m_p V_r f(Re_p)/T_p$ is the fluid drag force, where m_p is the mass of snow particle and V_r represents the relative speed between the snow particle and wind field, $T_p = \rho_p d_p^2/18\rho\nu$ is the particle relaxation time, and ρ_p is the density of the snow particle. $Re_p = d_p V_r/\nu$ is the particle Reynolds number, where d_p is the particle diameter and ν is the kinematic viscosity of air. $f\left(Re_p\right)$ can be expressed as (Clift et al., 1978):

$$f(Re_p) = \begin{cases} 1 & (Re_p < 1) \\ 1 + 0.15\,\mathrm{Re}_p^{0.687} & (Re_p \geq 1) \end{cases} \tag{4}$$

2.2 Mid-air collision model

The Lagrange particle tracking method is used to calculate the trajectory of each snow particle. Considering the fluid drag force and gravity, the governing equation of particle motion can be read as (Anderson and Haff, 1988;Lopes et al., 2013):

$$\frac{dx_{pi}}{dt} = u_{pi} \tag{5}$$

$$\frac{du_{pi}}{dt} = F_{di} + g_i\left(1 - \frac{\rho}{\rho_p}\right) \tag{6}$$

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where x_p and u_p are the position and velocity of snow particle, respectively, and g is the gravitational acceleration.

During the process of particle motion, the judgment criterion for a mid-air collision is $l < (d_A + d_B)/2$, in which $l = \sqrt{\sum (x_{Ai} - x_{Bi})^2}$ is the center distance of particle *A* and *B*. If particles *A* and *B* contact each other within a time step ($t, t + \Delta t$), there must exists a root δt ($0 < \delta t < \Delta t$) that satisfies the following relation:

$$\frac{d_A + d_B}{2} = \sqrt{\sum ((x_{Ai} - u_{Ai}\delta t) - (x_{Bi} - u_{Bi}\delta t))^2} \tag{7}$$

in which the smaller root will be used if two roots exist. Thus, the collision time of particles *A* and *B* is $t + \delta t$. To avoid repetition, there is the limitation condition of $x_{A1} < x_{B1}$.

To obtain particle information after the collision, the original coordinate system (X, Y, Z) is rotated to a new coordinate system (X_r, Y_r, Z_r), as shown in Fig. 1, in which the X_r axis points from the center of particle A to that of B. In this condition, only the particle velocity component along the X_r axis is changed after the collision.

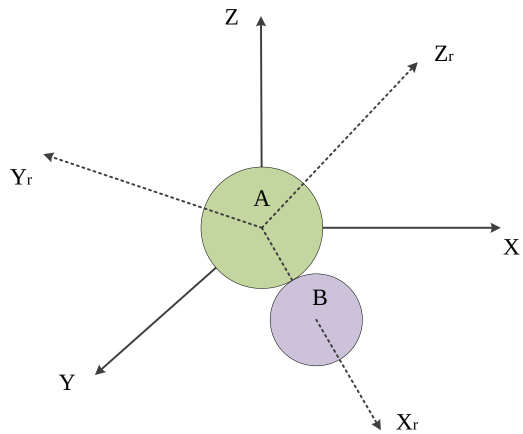

Figure 1. Schematic diagram of the rotation of the coordinate system.

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Then, the particle velocity components (u_{Aci} and u_{Bci}) in the new coordinate system can be calculated by the coordinate transformation algorithm. In addition, the particle velocity along the X_r axis after the collision in the new coordinate system can be expressed as:

$$\begin{cases} u'_{Ac1} = u_{Ac1} - \gamma d_B^3 (u_{Ac1} - u_{Bc1}) \\ u'_{Bc1} = u_{Bc1} + \gamma d_A^3 (u_{Ac1} - u_{Bc1}) \end{cases} \tag{8}$$

where $\lambda = (1+e) \big/ \left(d_A^3 + d_B^3\right)$ and $e = 0.51 v_n^{-1.4}$ is the recovery coefficient of ice (Supulver et al., 1995), in which v_n is the normal relative velocity of particle *A* and *B*.

Finally, the new coordinate system is rotated to the original location, and the particle velocity after the collision u'_{pi} can be obtained. The particle position after the collision can also be updated through $x'_{pi} = x_{pi} - u_{pi}\delta t + u'_{pi}\left(\Delta t - \delta t\right)$.

2.3 Simulation details

A computational domain of 2 m×1 m×1 m is adopted in this simulation. The grid number is 100×50×50, and grid stretch technology is used in the vertical direction (the finest grid scale is 2 mm). The turbulence inflow boundary is used (Lund et al., 1998), and the outlet is an open radiation boundary condition. The periodic boundary conditions are adopted along the spanwise direction. The inlet flow obeys the logarithmic wind profile with a boundary layer depth of 0.5 m and a roughness height of 3.0×10^{-5} m (Nemoto and Nishimura, 2004, 2001).

The aerodynamic entrainment scheme of (Zwaaftink et al., 2014) is used to induce a drifting snow in the turbulent boundary layer. In addition, the splash function for snow (Sugiura and Maeno, 2000) is used to describe the grain-bed interaction.

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Furthermore, the fracturing of the snow particle is not considered during particle collision, and the rotation of the particle is also neglected because the duration time of inter-particle collision is very short.

3 Results

3.1 Snow transport flux

The inter-particle collision within the drifting snow changes the trajectories of saltating particles, and further affect the structure and transport flux of the snow flow. Thus, the established drifting snow model is first verified by comparing the predicted snow transport flux with the measurements and other models.

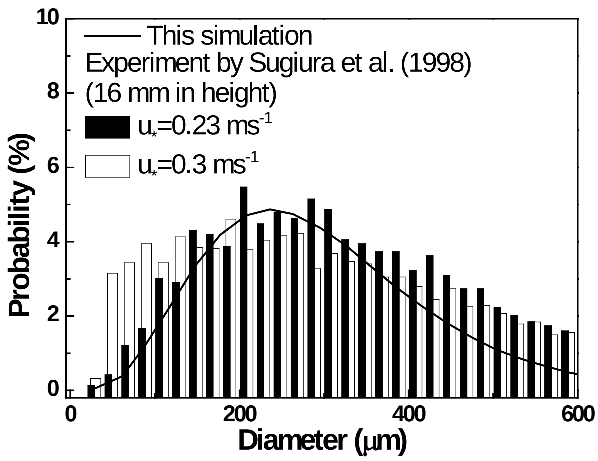

Figure 2. Particle size distribution in the simulation.

The particle size distribution of the snow sample is similar to that adopted by Nemoto and Nishimura (2004), as shown in Fig. 2, which follows the gamma function with a mean diameter of 250 μm. This distribution is also basically consistent with the experimental snow samples of Sugiura et al. (1998). Snow transport fluxes with and without a mid-air collision mechanism are shown in Fig. 3. From this figure, it

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can be seen that without mid-air collisions, the snow transport flux at various friction velocities are consistent with the simulation results of Nemoto and Nishimura (2004), mainly because the same splash function is adopted.

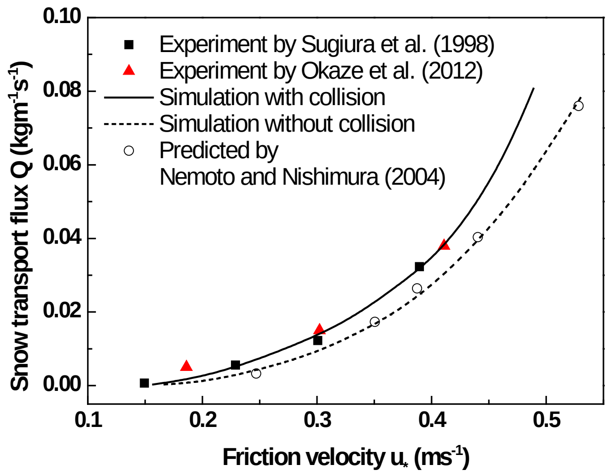

Figure 3. Snow transport flux versus friction velocity.

However, the snow transport flux is obviously enhanced with inter-particle collisions than without mid-air collisions, and the snow transport flux with mid-air collisions is obviously closer to the measurements (Okaze et al., 2012;Sugiura et al., 1998), which indicates that mid-air collisions are not negligible within drifting snow. At the same time, the enhanced proportion increases with increasing friction velocity. For example, at approximately the critical friction velocity, the snow transport flux with and without mid-air collisions is almost equal. However, when the friction velocity reaches 0.489 ms^{-1}, the enhanced proportion by mid-air collisions is up to 38.97%. The reason could be that frequent collisions between higher and lower particles in the snow flow, on the one hand, increase the momentum of the impacting particles, and on the other hand, send the falling particles back to high altitude to

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obtain more energy.

3.2 Collision frequency

The collision frequency under various friction velocities is shown in Fig. 4. It can be seen that the collision frequency is directly related to the particle concentration. When the particle concentration is below 1.0e6 m^{-3}, inter-particle collisions rarely occur. However, with the further increment in the particle concentration, the frequency of the inter-particle collision event increases rapidly, and one particle may experience over 10 collisions per second when the particle concentration is 1.0×10^{8} m^{-3}.

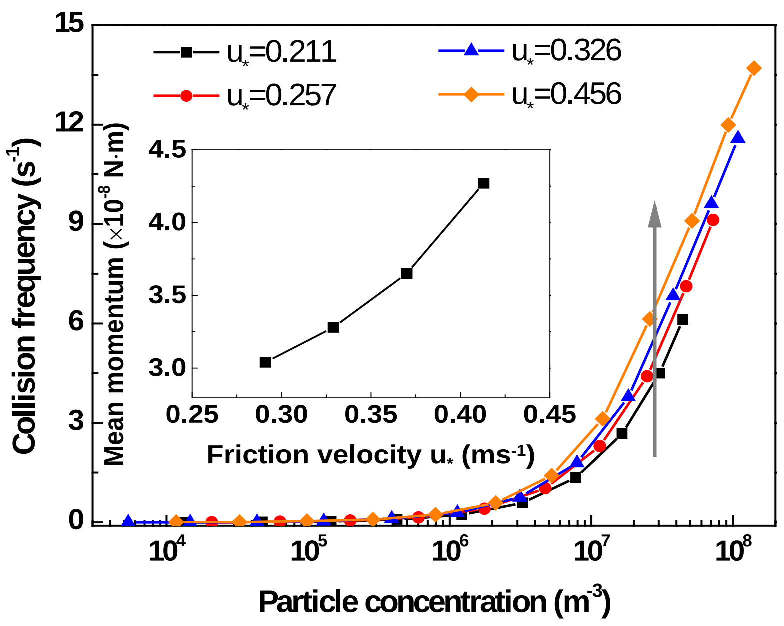

Figure 4. Inter-particle collision frequency versus particle concentration under various friction velocities (inset: mean particle momentum of saltating snow particle in drifting snow).

In addition, the collision frequency also increases with the friction velocity at the same particle concentration. The reason could be that particles are more active with

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larger friction velocity, and as shown in the inset, the mean particle momentum tends to increase with friction velocity, which is also consistent with the experimental measurements (Nishimura et al., 2015;Nishimura and Hunt, 2000).

From the above analysis, drifting snow generally exists at a critical height, i.e., mid-air collisions frequently occur below this height, while there are few collision events above this height. As shown in Fig. 5, the critical height h_c basically increases linearly with the friction velocity when the critical particle concentration of 1.0e6 m^{-3} is adopted, and the function of $h_c = 1.42 + 20.8u_*$ properly describes the tendency.

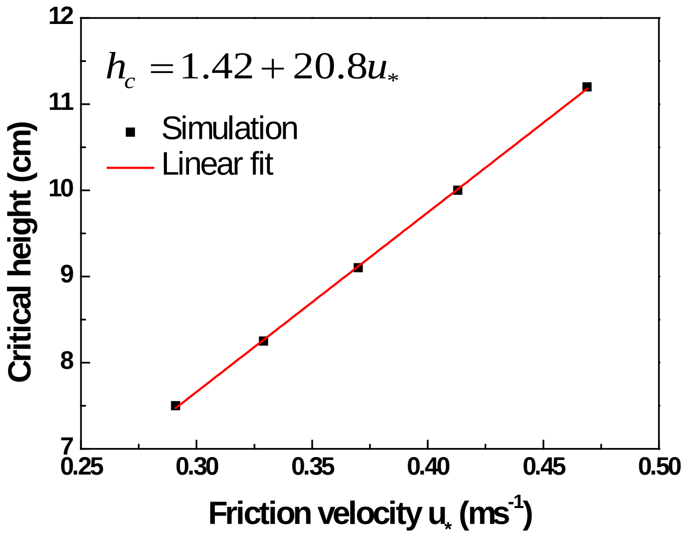

Figure 5. Critical height for the mid-air collision in drifting snow.

4 Discussions

In steady-state drifting snow, part of the downward horizontal momentum flux in the saltation layer is carried by saltating snow particles, and thus the total downward momentum flux τ equals the sum of the horizontal momentum fluxes due to particles

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τ_p and the fluid τ_f, that is, $\tau = \tau_p + \tau_f$ (Kok et al., 2012;Raupach, 1991). The residual fluid shear stress τ_f, also called the impact threshold, represents the threshold of the fluid shear stress that retains the particle splash process and is commonly treated as a constant in the steady-state saltation (Bagnold, 1941;Owen, 1964).

However, several recent physically based numerical saltation models indicate that τ_f in fact decreases with the friction velocity mainly because the larger wind speed higher in the saltation layer should be compensated by a decrease in the wind speed lower in the saltation layer (Kok et al., 2012). This is also true for drifting snow, as shown in Fig. 6(a). In this simulation, coarse snow particles are adopted since pure saltation with least suspended snow is wanted, the particle size distribution is shown in Fig. 6(b). It can be seen that the particle size is larger than 100 μm because the diameter of the suspension snow is basically smaller than 100 μm (Gordon and Taylor, 2009;Huang and Wang, 2015;Nemoto and Nishimura, 2004;Nishimura and Hunt, 2000).

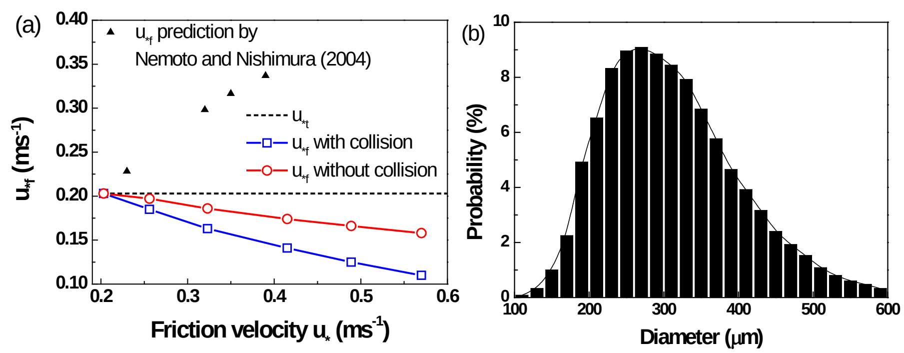

Figure 6. (a) Variation in the fluid stress versus friction velocity, and (b) particle size distribution for the pure saltation simulation.

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Additionally, the presence of mid-air collisions further decreases the impact threshold to a great extent. As shown in Fig. 6(a), under the same friction velocity condition, the residual fluid shear stress τ_f with the mid-air collision effect is smaller than that without mid-air collisions, mainly because frequent inter-particle collisions can produce many high energy particles under the actions of momentum transfer among the particles and thus enhances saltation.

It is known that the saltation mass flux can be derived from the momentum balance in the saltation layer as (Kok et al., 2012;Sørensen, 2004):

$$Q = \rho\left(u_*^2 - u_{*f}^2\right)L / \Delta\bar{V} \quad (9)$$

where u_{*f} is the critical impact friction velocity, L is the mean saltation length, and $\Delta\bar{V}$ is the mean velocity difference of the impact and lift-off particles. Many numerical and experimental investigations present the scaling of the saltation mass flux Q with u_*^3 (Bagnold, 1941;Clifton et al., 2006;Nishimura and Hunt, 2000;Owen, 1964;Vionnet et al., 2013) by assuming that the particle speeds can be linearly scaled with the friction velocity u_*, and u_{*f} is commonly approximate with the critical fluid friction velocity u_{*_t}. Whereas the critical impact friction velocity u_{*f} may be larger or smaller than the critical fluid friction velocity u_{*_t} as a matter of fact, as shown in Fig. 6(a).

For wind-blown sand movement, recent studies have proved that the saltation mass flux actually shows a quadratic dependency with the friction velocity since the mean particle speed in the saltation layer is independent of the friction velocity (Durán et al., 2011;Ho et al., 2011;Kok et al., 2012). For drifting snow, however, the

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mean particle speed at the near surface is essentially proportional to the friction velocity (Nishimura and Hunt, 2000;Nishimura et al., 2015) probably due to the smaller response time of the snow particle, which supports the fact that the snow saltation flux typically shows a cubic dependency.

Interestingly, Nemoto and Nishimura (2004) reported an increasing tendency of the fluid stress τ_f with the friction velocity when suspension snow is included, as shown in Fig. 6(a). This increase may be because suspended snow reduces the wind speed higher in the air, which in turn need a larger wind speed lower in the saltation layer to replenish the particle momentum. Thus, the suspension snow may restrain the saltation movement. The measurements of Nishimura and Hunt (2000) with various snow grain sizes also support this point.

In this way, the saltation mass flux (or residual fluid stress) of drifting snow largely depends on the particle size. For pure saltation movement as in above simulation (e.g., coarse grain size), τ_f decreases with the friction velocity and results in a larger saltation flux. Whereas for drifting snow with considerable suspended snow particles, τ_f may increase with friction velocity, and thus reduce the saltation mass flux. That is, snow samples with different grain sizes may have different saltation mass fluxes under the same wind condition. The particle borne stress τ_p from the above simulation is approximately 4.5 times that predicted by the model of Nemoto and Nishimura (2004) when the friction velocity is 0.39 ms^{-1}, and thus, the snow saltation flux may be considerably different.

Most previous drifting snow models adopted by the mass balance studies of glaciers of ice caps consider the saltation and suspension processes independently (Gallée et al., 2001;Lehning et al., 2008;Vionnet et al., 2013). From above analysis, this may increase the uncertainty of prediction with varying grain sizes. A coupling model that includes the interactions between saltation and suspension snows is necessary to model the drifting snow process more exactly.

5 Conclusions

In this work, a three-dimensional drifting snow model in the turbulent boundary layer with consideration of a mid-air collision mechanism is established based on tracking the trajectory of each snow particle; this model enables the exploration of the mid-air collision mechanism on the drifting snow process exactly.

In the traveling snow flow, mid-air collisions play an important role in enhancing the snow transport flux. In addition, there exists a critical particle concentration in which inter-particle collisions rarely occur below this value. However, above the critical concentration, the collision frequency as well as the role of inter-particle collisions is found to increase with the friction velocity.

Furthermore, mid-air collisions also enhances the particle activity, and thus further reduces the residual fluid stress during drifting snow conditions. The snow saltation flux is also found to be sensitive to particle size distribution of the snow samples because suspension snow may restrain saltation movement to a great extent, and the snow saltation flux may vary several times for different particle size distribution.

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