Photo: A. Christen

19 Momentum exchange

Learning Objectives

- Describe forces that deform surface objects and air parcels.
- Explain how momentum is exchanged in the ABL.
- Describe and quantify momentum transfer in the ABL.

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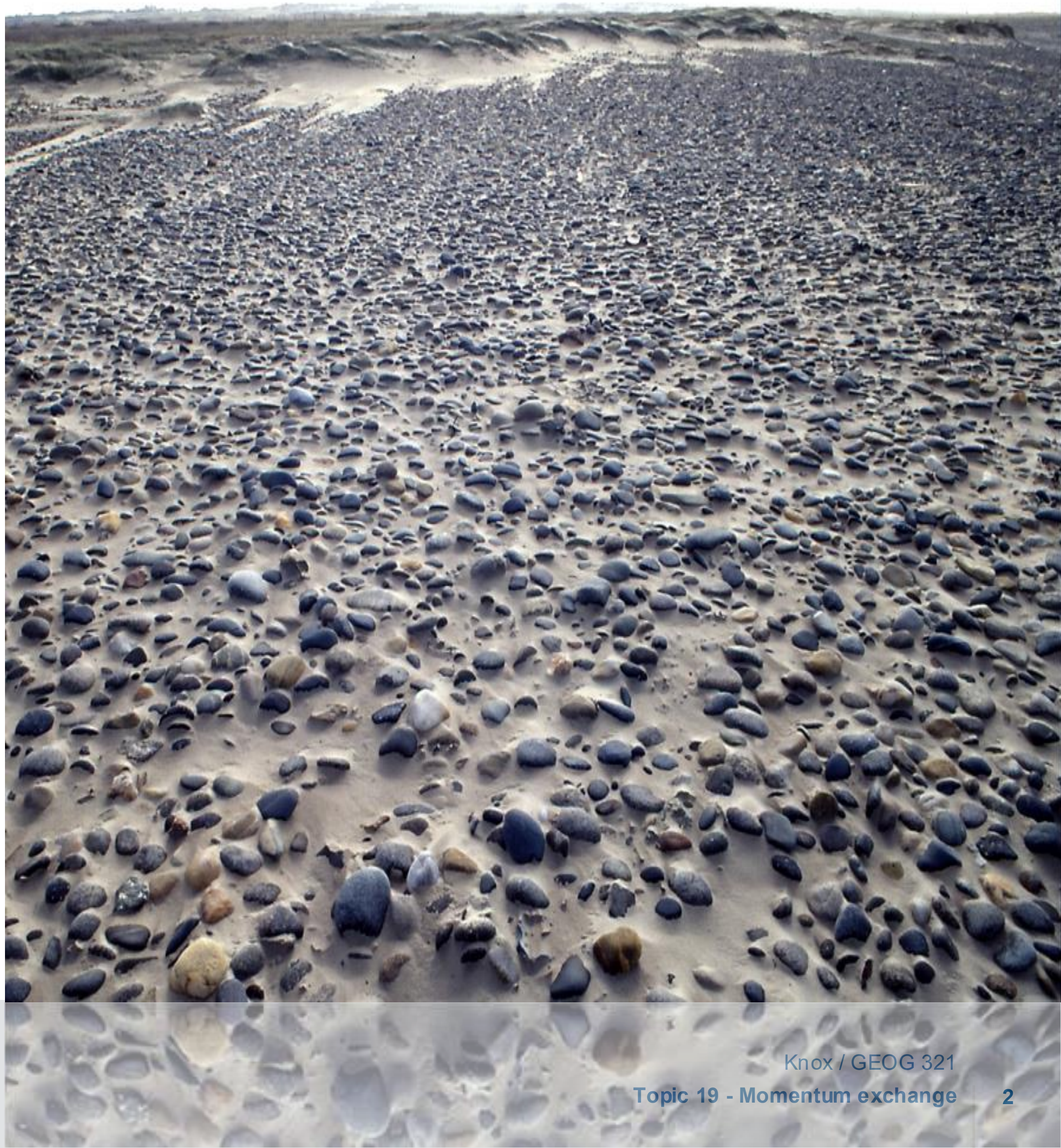


Motivation

Atmospheric motions create forces that deform the atmosphere itself, deform and damage objects, and create waves on water surfaces.

Wind damage in Stanley Park 2006
'branch lines', 18, 2007

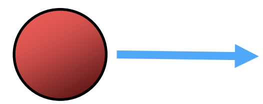
Photo: A. Christen

Mechanics review - what is momentum?

Momentum $m\overline{u}$ (kg m s^{-1})

mass

horizontal wind

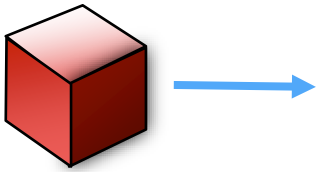


In the atmosphere:

Horizontal momentum <u>per unit volume</u> $\rho\overline{u}$ (kg m^{-3} m s^{-1} = kg m^{-2} s^{-1})

mass in one m^3

horizontal wind



Drag

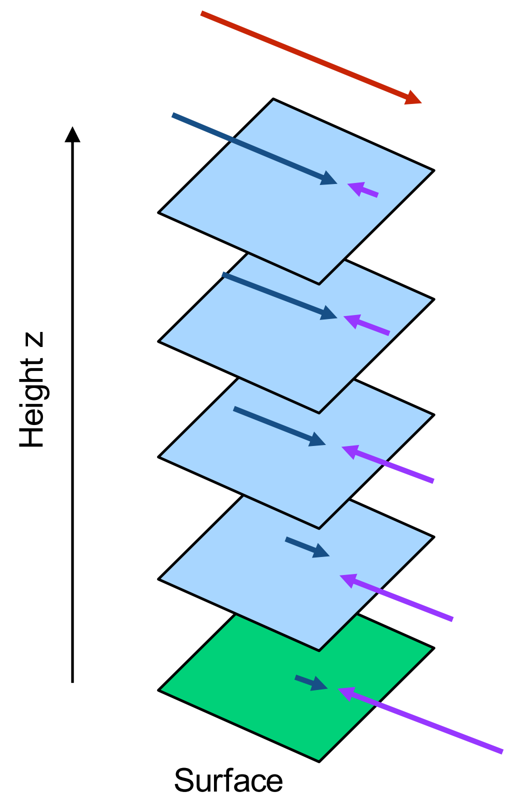
For a fluid to move, we require a **horizontal force** in the direction of the mean flow. Usually this is the pressure gradient force.

In the ABL there is an opposing force by the solid surface, which slows the wind, at least its lowest portion and it is called **drag force**.

The drag force can be caused by form drag and skin drag.

Drag slows motion close to the ground and gives rise to a sharp decrease of mean horizontal wind speed as the surface is approached.

The force exerted on the surface by the air being dragged over it is called the surface **shear stress**.



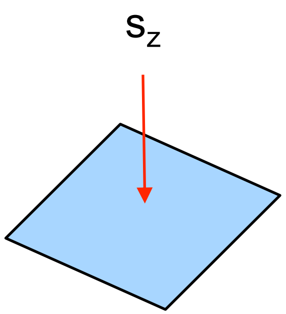
Stress

In a general sense, stress is a **force** tending to **deform a body**, expressed as force per unit area.

There are forces acting **normal** and **tangential** to a surface.

Normal stress (e.g. pressure)

normal force per unit area



Tangential stress (i.e. shear stress)

tangential force per unit area

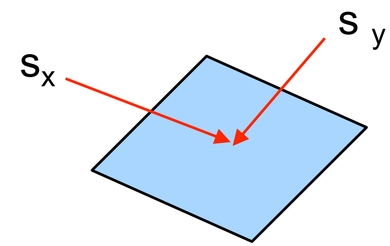


Photo: A. Christen

Stress in the atmosphere

In the atmosphere, three particular forms of stress are acting on an air parcel:

- Pressure
- Viscous shear stress
- Reynolds stress

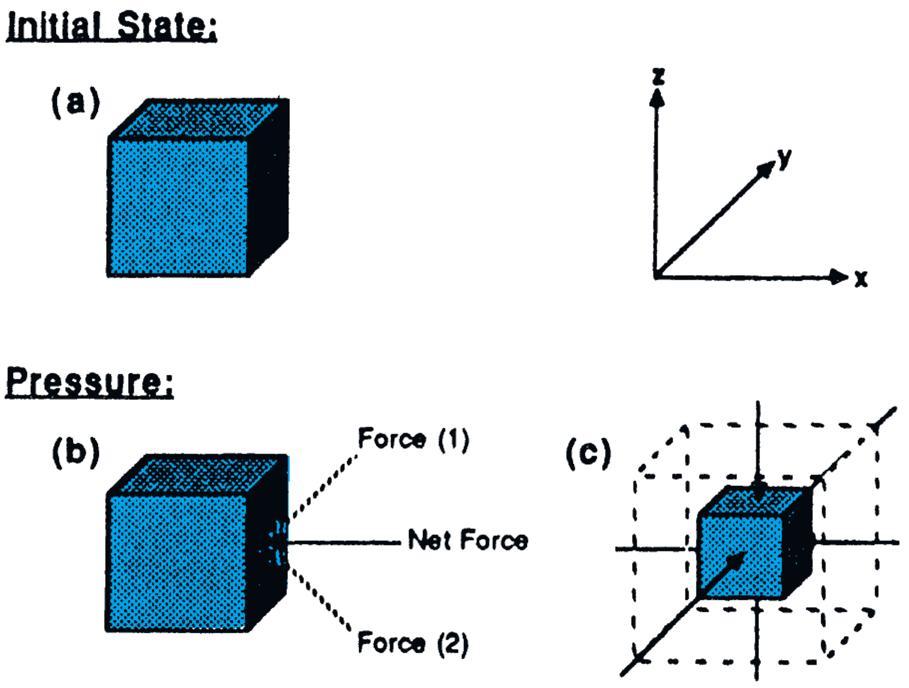
Photo: A. Christen

Pressure

Pressure can act on an air parcel at rest.

At a point, pressure acts isotropically and normal to the surface (normal force per unit area). Because it is not dependent on direction, pressure can be reduced to the scalar p.

Pressure changes always result in an isotropic compression or expansion of an air parcel.



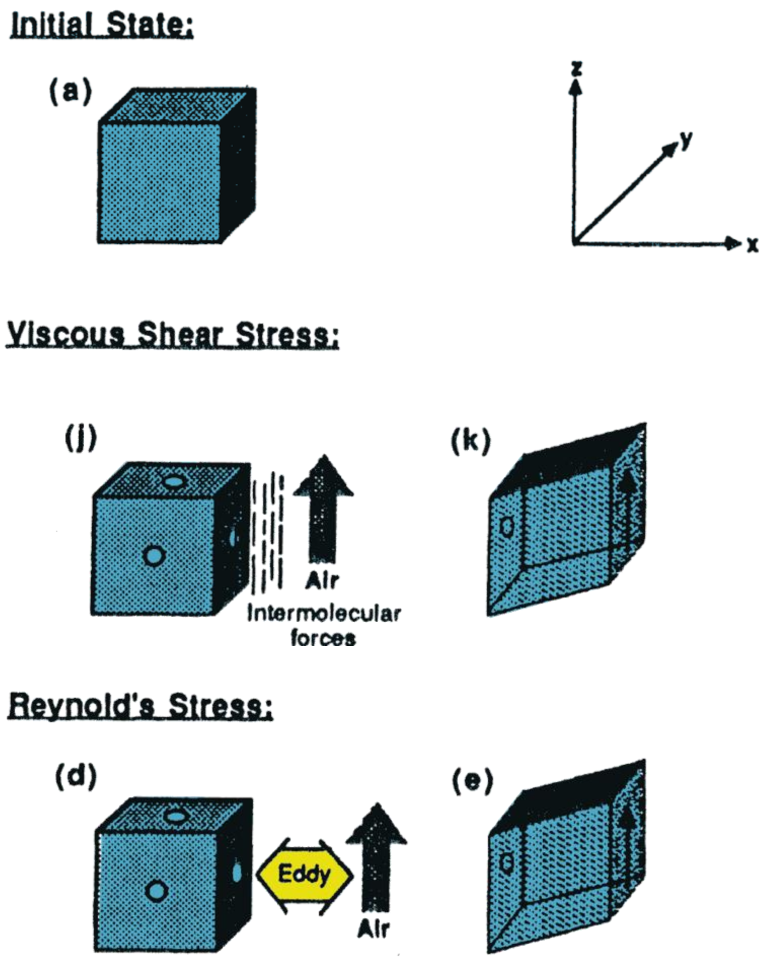
R. B. Stull (1988): 'An introduction to boundary layer meteorology'

Viscous shear stress vs. Reynolds stress

Total shear stress

Viscous shear stress is important whenever there are shearing forces in a moving fluid (laminar or turbulent). These shearing forces are opposed to the intermolecular forces. Viscous stress is a function of the velocity gradients and the dynamic viscosity.

Reynolds stress is only found in turbulent flows. It is a result of convective movement of momentum surplus and momentum deficit eddies within the fluid.



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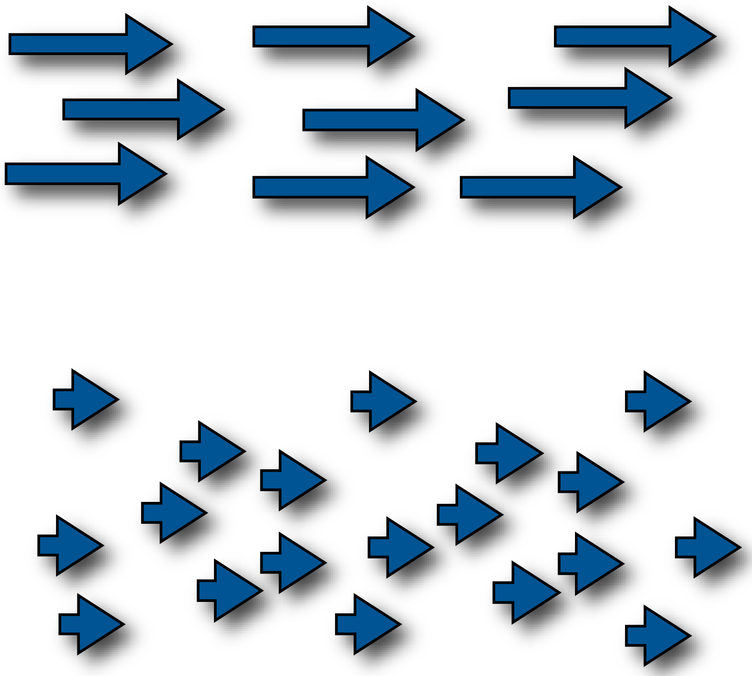
Reynolds stress

The flux of momentum is accomplished through random motion. Discrete 'lumps' (eddies) of the fluid are displaced by turbulence over a distance and there merge with the flow. Consequently eddies transport their momentum surplus or their momentum deficit ($\rho\overline{u}$) across a distance.

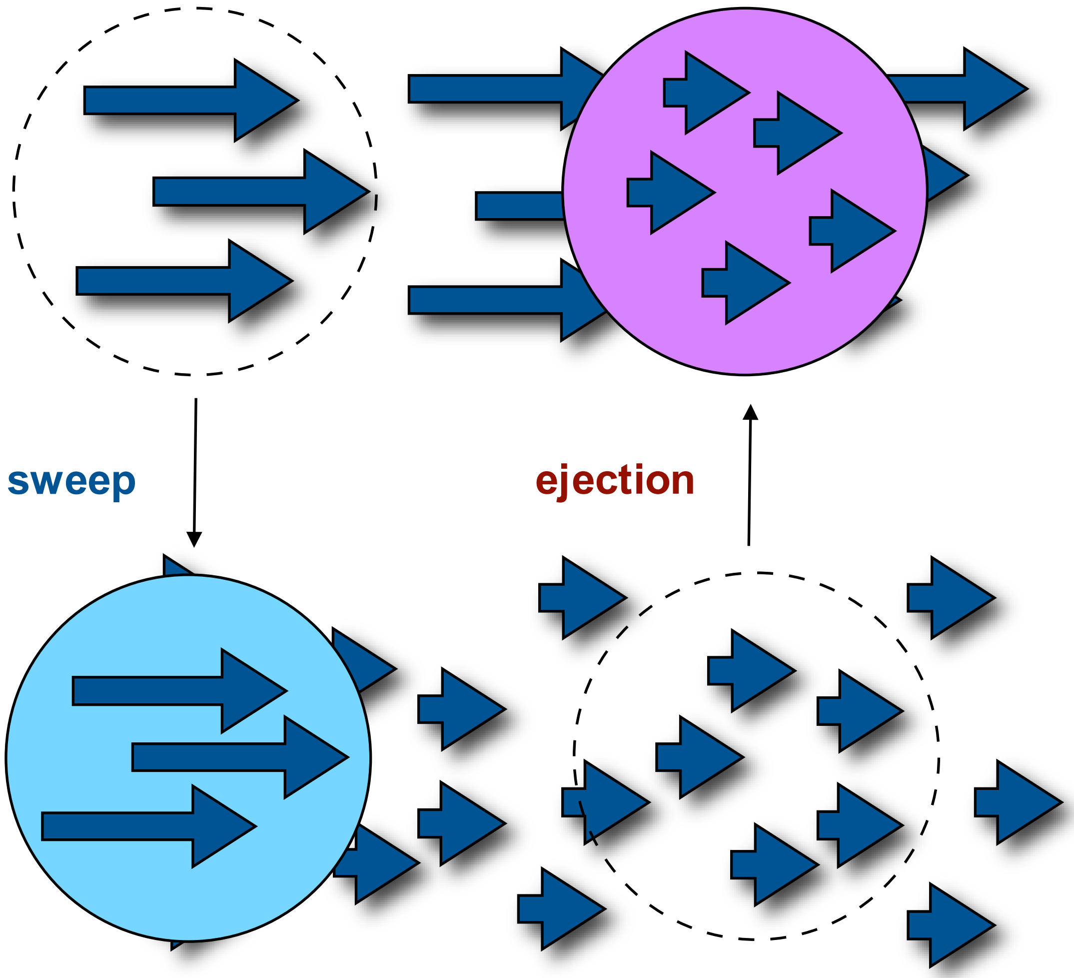


Sweeps and ejections

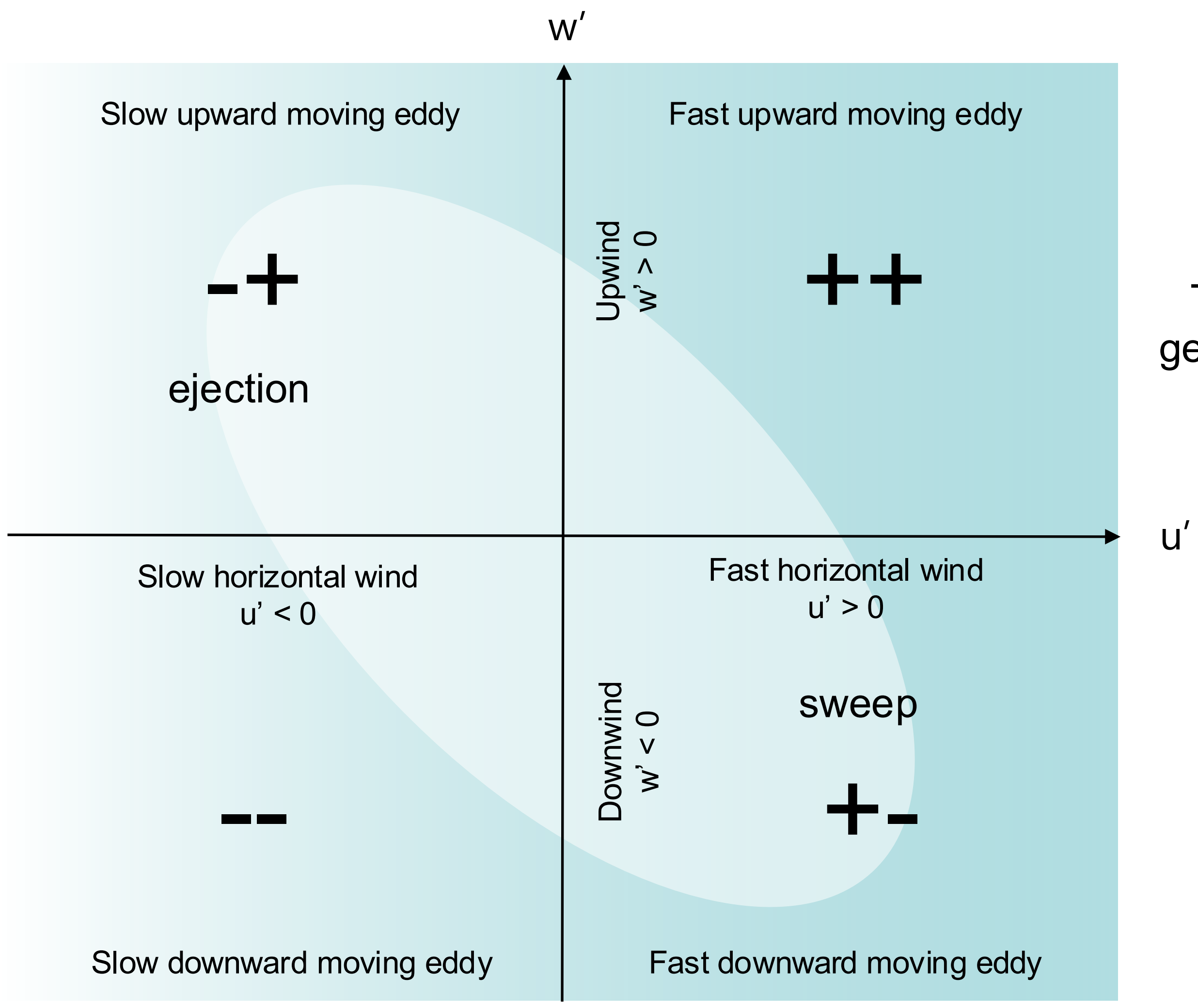
In the atmospheric boundary layer over flat terrain the transfer can be often simplified 1-dimensional (up/down only)

Events transporting momentum surplus downward are called **sweeps**.

Events transporting momentum deficit upward are called **ejections**.



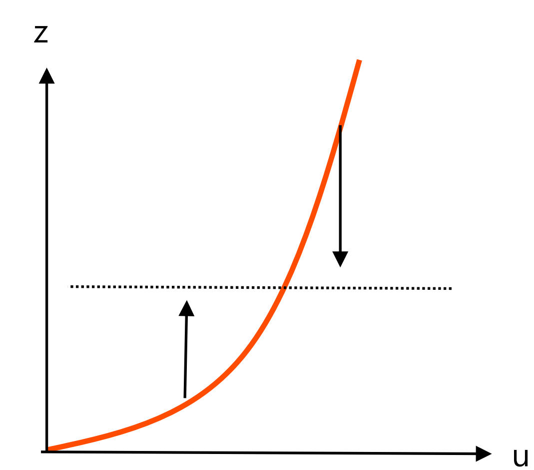
Momentum exchange - statistically approached



$$\overline{u'w'} < 0$$

Momentum flux is directed towards the surface

The surface layer, influenced by friction, generates this shearing force and transmits it downwards as a flux of momentum



Horizontal wind speed increases with height.

Reynolds stress and covariance

If an eddy merges it imports/subtracts $\rho u'$ amount of horizontal momentum per unit volume from/to the flow at level z.

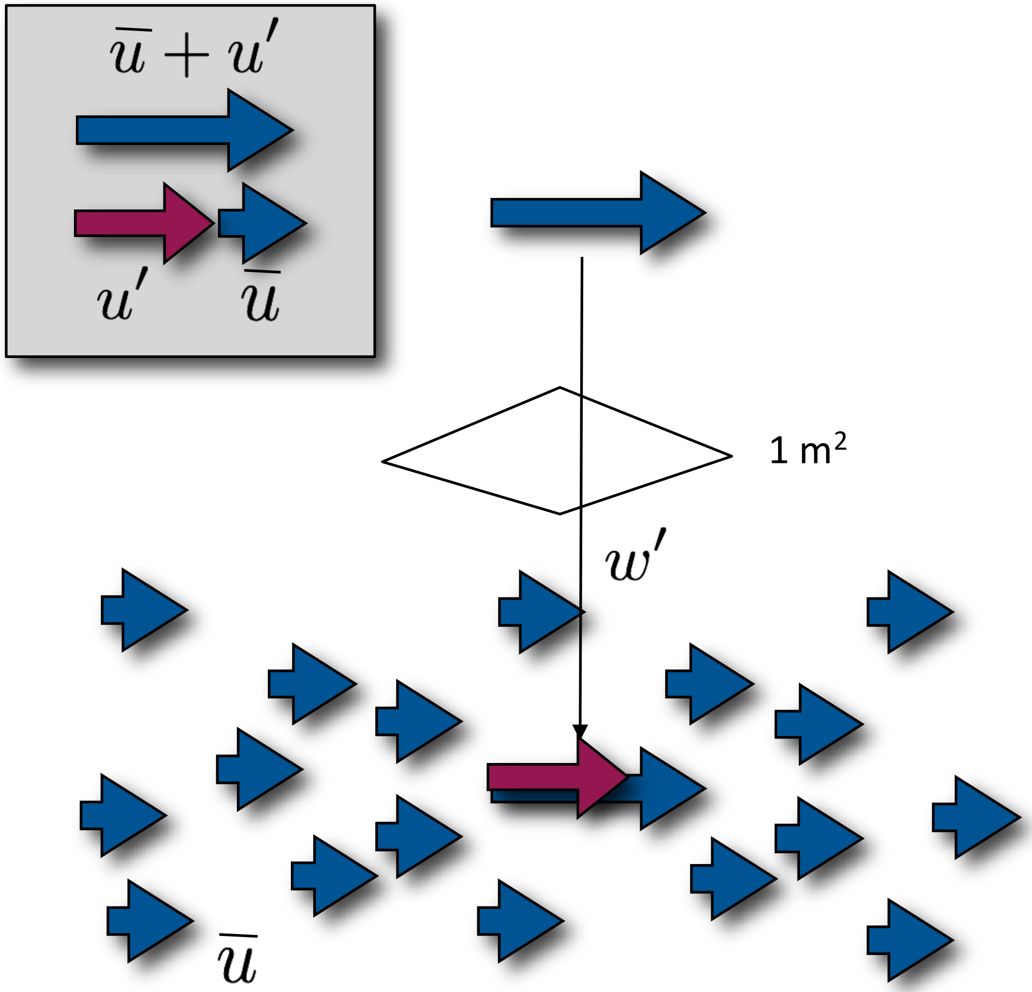
If the vertical velocity of the eddy is w' then the instantaneous Reynolds stress (momentum flux) is

$$\tau = -\rho\, u' w'$$

and in the time average

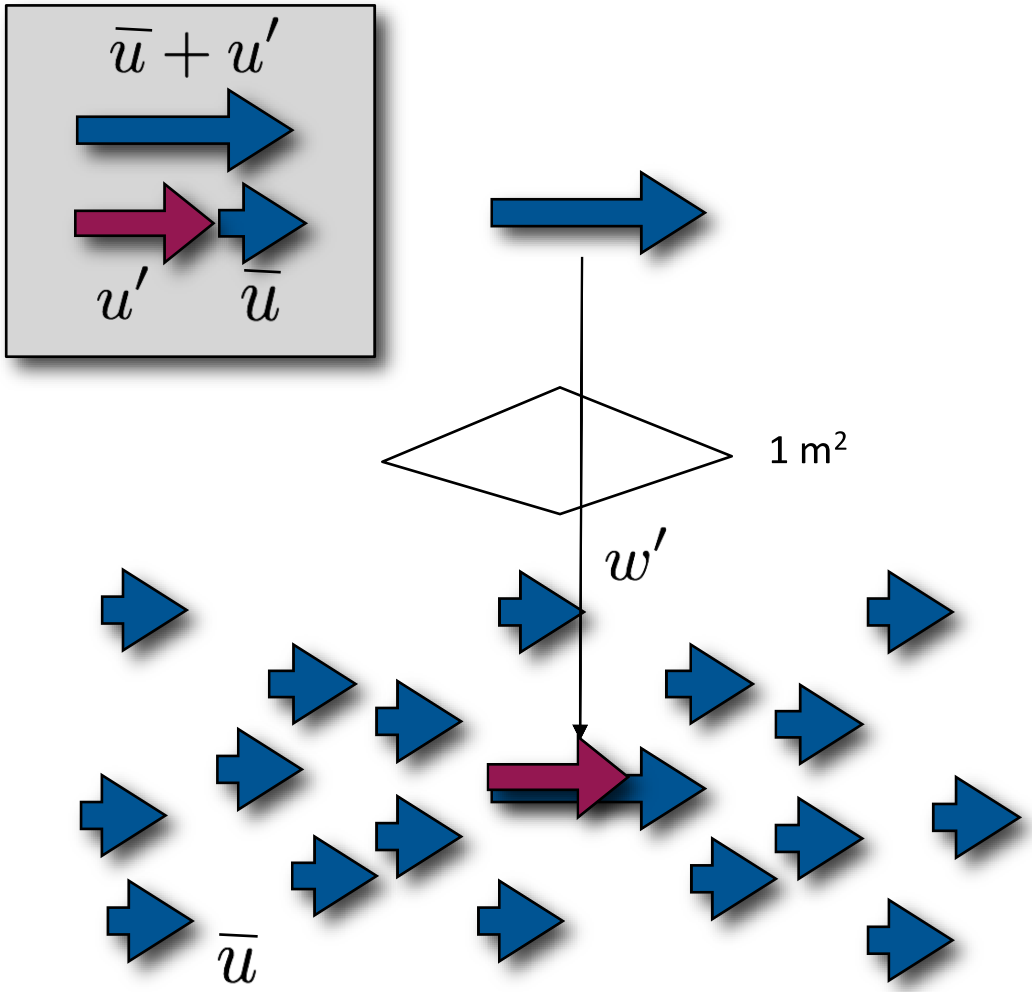
$$\tau = -\rho\, \overline{u' w'}$$

(this assumes horizontal homogeneous conditions)



Vertical flux of horizontal moment = Horizontal shear stress

- The **direction of transport** (flux)
- The **direction of force** (stress)



Friction velocity

In turbulent shear flows, the Reynolds stress (momentum flux) is found to be proportional to the square of the mean flow velocity, which leads to the definition of the **friction velocity** u_* (units: m s^{-1})

$$u_*^2 = \frac{\tau_0}{\rho}$$

Close to the surface, we can assume and write $\tau = \tau_0$

$$\tau \approx \rho u_*^2$$

And because

$$\tau = -\rho \overline{u'w'} \qquad \star$$

A reasonable well estimate of the friction velocity can be made from measurements of the Reynolds stress $\overline{u'w'}$ close to the surface, i.e.

$$u_* \approx \sqrt{-\overline{u'w'}} \qquad \star$$

(this assumes again horizontal homogeneous conditions and a measurement height close to the surface)

Take home points

- There are **tangential** and **normal stresses** that deform an air parcel in the atmosphere.
- Sweeps and ejections refer to part of eddies in a turbulent flow that move momentum up and down.
- Momentum transfer can be quantified using the **covariance** $\overline{u'w'}$ and **friction velocity** u_* is a global parameter that describes its square root in the lowest surface layer.