INTERMITTENT TURBULENT SUSPENSION EVENTS OVER SAND DUNES 
ON THE BED OF THE FRASER RIVER, NEAR MISSION, BRITISH COLUMBIA.

By

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Intermittent turbulent suspension events over sand dunes on the bed of the Fraser River, near Mission, British Columbia.

ABSTRACT

The purpose of this study is to gain some first insights into the role of burst-like turbulent motions in sediment suspension over a sandy channel bed, during typical conditions of strong sediment transport with active bedforms. The focus is the suspension mechanism that maintains sizeable sediment concentrations away from the bed, where much of the downstream transport occurs, rather than entrainment at the sediment boundary itself.

Flow components downstream and normal to the mean boundary, along with the output of an optical suspended sediment sensor, were monitored 1 m above the bed. The main study data were collected in a 10 m deep channel of the Fraser River near Mission, British Columbia, Canada. Velocities averaged 1.4 m/s at the surface and 0.9 m/s at the sensors, where mean suspended sediment concentrations were 500 mg/l; decimetre height small dunes on the backs of larger, metre amplitude dunes covered the channel bed. Many hours of data were recorded at 5 Hz, allowing multi-second scale turbulent motions as well as multi-minute oscillations to be resolved in both the velocity and turbidity records.

Burst-like "ejection and inrush" motions were identified, producing a high degree of intermittency in momentum exchange: 80% of the mean Reynolds stress at the 1 m level is produced during 12% of the record duration. The burst recurrence period appears to be significantly greater than predicted by applying the conventional outer flow scaling in this environment. It is hypothesised that the non-uniform shear and pressure gradient conditions over the various scales of bedforms on the river floor may somehow affect mean burst periodicity, modifying the recurrence scaling developed over flat boundaries. The determination of a burst recurrence timescale from one-point data is inherently imprecise however and, as elsewhere, a
continuous variation of return periods with relative magnitude of extreme \((u'v')\) events is observed.

The optical turbidity (OBS) time series reveals that these intermittent burst-like motions are, as expected, very important in vertically mixing sediments across the 1 m level in the flow; for example violent ejections, occurring only 1\% of the time and contributing some 10\% to mean turbulent momentum flux, appear to account for 6\% of the total vertical sediment flux. The statistical association between the momentum and sediment mixing efficiencies of any ejection appears to be only moderately strong, however; very intense suspension can be associated with rather "weak" ejections (in terms of stress), and vice-versa. Differences between momentum and sediment mixing effects of a given ejection may partly be related to the "crossing trajectories effect"; sand grains continually fall out of the eddies that bear them, so the momentum and sediment "contents" of an eddy at 1 m off the bed are not perfectly linked.

Turbulent sediment suspension is, like momentum exchange, a highly intermittent process in itself. After selecting turbulent events only for suspension efficiency, the largest ones, occupying only 5\% of the time, contribute approximately one half of the total vertical sediment flux. There is no indication that the conventional scaling of burst recurrence corresponds to the occurrence of any distinctive event level for suspension. Interestingly, burst-like turbulent motions are not the only flow oscillations contributing to suspension in the high flow conditions of the study. Multi-minute period flow perturbations at 1 m off the bed significantly assist burst-scale turbulent motions in driving the upward sediment mixing.

In summary, turbulent mixing of both momentum and sediment at 1 m over a typical sandy river bed is dominated by intermittent, intense "burst-like" events. However, the extrapolation of intermittent "bursting" concepts and structural constants from small-scale laboratory flows to the larger fluvial environment may be misleading.
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CHAPTER 1  INTRODUCTION

The investigation over recent decades of coherent bursting structures in wall bounded shear flows has brought a new perspective to the study of alluvial sediment transport. Although long parameterized by mean boundary shear stress, bed material transport processes are known to depend on near-bed turbulent velocity fluctuations and resultant instantaneous drag and lift forces. Turbulent bursting is a prevalent working model to understand and quantify large near-bed turbulent motions. The details of the stochastic bursting events and their dependence on the parameters of the overall flow are however complex and still imperfectly understood. Moreover the interaction of these turbulent structures with deformable sediment boundaries constitutes a vast area for future research. Sediments on natural stream beds display a range of particle sizes and fall velocities affecting their susceptibility to entrainment by eddy motions. They also become arranged into a variety of bedforms that themselves modify the shear flow and turbulence generation.

A brief critical review of this research context will be presented. It will be shown that, to date, only preliminary insights into the broad significance of turbulent bursting to alluvial sediment transport have been gained, essentially for lack of direct observations of these phenomena in strong river flows. The study reported here aims in particular to investigate a long-standing conjecture in the fluvial literature about the importance for suspended sand transport of "macroturbulent" vertical eddy motions (visualised in "boils" and now often identified with bursting; Matthes, 1947; Coleman, 1969; Jackson 1976). Casual observation of
sands brought violently to the surface in "boils" suggests to some
that burst-like motions may dominate overall sediment suspension.
Conceptual models linking turbulent bursting, suspended sediment
transport and alluvial bedforms have found their way into textbooks
(e.g. Allen, 1985), despite not having been directly tested in the
fluvial environment.

This study will focus on turbulent suspension processes in a
sandy fluvial environment, as they occur over active dune bedforms.
The main emphasis of the study will be on the timing and the
contribution to momentum exchange as well as sediment suspension of
intermittent "burst-like" events, monitored at 1 m from the bed, in
a large river channel with active dune field, and under high flow
conditions. The key objective will be to assess the importance to
suspension (relative to the mean vertical sediment flux) of the
"burst-like" turbulent events at that height in a 10 m deep river
flow. A thorough study of the relation of such burst-like events to
"classic" laboratory bursting will not be attempted here; it would
require a more extensive set of flow data than could be generated in
this study.

1.1 Bursting in laboratory and large-scale flows.

Starting in the 1960s with eddy visualization studies of
motions in the near-wall zone, where much of the turbulence
production in boundary layers was known to occur (e.g.: Kline et
al., 1967), much research on turbulent bursting has been conducted
in the last decades. Cantwell (1981) provides a survey of the
general field of coherent motions in turbulent flows that developed
from these early findings. In outline, a characteristic sequence of
events is observed to occur in the near-wall zone of boundary layers
in laboratory flows: it involves deformation of streamwise, low-
speed "streaks" in the viscous sublayer and eventual violent
"ejections" of these relatively slow parcels away from the wall, as
part of "bursting" motions reaching typically as far as the outer
zones of the boundary layer. Completing the bursting sequence (and maintaining continuity of mass) are "sweeps" of faster fluid that move down towards the wall. Such intermittent, violent motions are seen to account for much of the momentum exchange and turbulence production in the boundary layer.

Although a coherent sequence of events is observed, these occur randomly in space and time. There appears to be however an average recurrence period for strong bursting events at any point in the flow, and this period is fairly constant across much of the boundary layer. Unfortunately, estimation of burst recurrence statistics remains a vexed issue (Bogard and Tiederman, 1986); it depends on the type of signal available (whether flow visualization movies or simple Eulerian velocity records) and on various procedures of filtering or conditional sampling. It also depends strongly on subjective decisions as to event thresholds. Such complications mar the interpretation of burst recurrence data from large-scale geophysical flows (such as are studied here). There is some agreement however that the burst recurrence period $T_b$ appears to scale with the "outer variables": free-stream velocity $U_s$ and boundary layer thickness $H$ (Rao et al., 1971; Willmarth and Lu, 1974).

\begin{equation}
T_b = a*(H/U_s), \text{ where } a \text{ is in the range 3 to 7}
\end{equation}

Much of the subsequent fluid mechanics research in this area has concentrated on elucidating the relations between the near-wall instabilities and "outer flow" events such as turbulent bulges or "boils" in free surface flows (e.g.: Falco, 1977; Brown and Thomas, 1977; Nakagawa and Nezu, 1981). In particular, physical models have been proposed to explain the triggering of minute inner flow instabilities at a rate set by bulk flow events and parameters (as suggested by (1)) and, conversely, the controls that seem to allow only certain of these instabilities to grow to the scale of the flow thickness.
Streaks in the viscous sublayer were seen to play a large role in the genesis of bursting over smooth, flat boundaries in the laboratory. Yet in most natural fluid flows the viscous layer is severely disrupted by the large scale of boundary roughness. Hence it was natural to ask whether bursting also occurred over rough, non-planar surfaces, in particular sedimentary beds. Grass (1971) demonstrated that burst/sweep motions occurred over rough, sandy or gravelly, as well as smooth surfaces in the laboratory. In the absence of a viscous sublayer, ejections were observed to originate from the interstices of the sediment bed.

Natural river flows have, however, Reynolds numbers based on flow depth that are typically 2 orders of magnitude higher than those encountered in the laboratory studies, where bursting events have been investigated extensively. River boundaries are often marked by complex bedform arrangements, that can modulate the flow through most of its full depth. Detailed confirmation, through flow visualization, of the existence of 3D "bursting structures" analogous to those studied in the laboratory, is still lacking in high Reynolds number geophysical flows. Such visualisation may have to wait for new remote-monitoring techniques of the 3D turbulent field (e.g. by acoustic Doppler techniques) to be developed for these environments. Rood and Hickin (1989) speculate that eddy shedding in the lee of bed dunes, rather than bursting-related disturbances, may be mainly responsible for large-scale suspension motions resulting in surface boils in sand bed rivers.

A number of field studies have suggested, nonetheless, that burst-like processes are active at geophysical scales. Turbulence measurements, conducted at 1 to 2 m from the bed in benthic and tidal boundary layers, reveal intermittent events with characteristics akin to those of laboratory bursting, at least as far as observations at one position within the flow can disclose (Gordon, 1975; Gordon and Witting, 1977; Heathershaw, 1974, 1979; Anwar, 1981; Anwar and Atkins, 1982). These studies essentially rely
on recorded \((u'v')\) signals \((u'\) is the fluctuation in streamwise velocity and \(v'\) that in the velocity normal to the boundary); this \((u'v')\) product is often interpreted as an instantaneous contribution to horizontal momentum exchange (shear stress) across the layer. In most cases it was found that, as in laboratory bursting, much of the mean stress was produced by brief but intense (thus "intermittent") "ejection and inrush" events. This type of analysis is at the heart of my study.

Clear confirmation, for such "burst-like" events in geophysical flows, of the recurrence scaling observed in the laboratory (1) has not always been possible however: while laboratory research has pointed out the sensitivity of burst counts to the selection of the event-defining threshold (Willmarth and Lu, 1974), in many field studies of \((u'v')\) events no explicit justification of the choice of event threshold was provided. Results can be hard to interpret unless great care is taken to set the "event"-defining threshold objectively and consistently.

Considerable sophistication is involved in defining and counting bursts in controlled laboratory conditions and using multi-point data (e.g. Rao et al., 1971; Lu and Willmarth, 1973; Willmarth and Lu, 1974; Bogard and Tiederman, 1986). One-point \((u'v')\) series from large scale flows do not appear to be easier to interpret. McLean and Smith (1979) claim not to have been able to identify conspicuous burst-like \((u'v')\) events liable to such a recurrence analysis near the bed of the Columbia River (no clear threshold was perceived between the different levels of intense events and the lower intensity background). Heathershaw (1979) did not produce direct counts of bursting events in Irish Sea tidal flows, but inferred return periods through derived estimates of intermittency and burst duration. Gordon (1974, 1975) defined a burst counting threshold level equal to twice the median \((u'v')\), but did not otherwise justify this choice. Anwar (1981) also failed to discuss his choice of threshold and arrived at a burst recurrence period in a tidal flow much below the values predicted by outer flow scaling.
1.2 Bursting and sediment transport.

The potential effectiveness in terms of sediment entrainment of energetic "sweeps" bringing high velocities to the bed, as well as that of ejections of near bed fluid in suspending sediment, are both immediately obvious. Early detailed observations of sediment motion by Sutherland (1967) had revealed the role of eddies impinging on a sand bed in both entraining and suspending particles. Later flow visualization work by Grass (1970, 1971, 1974) clearly suggested a complementarity of sweeps and ejections in transporting sands. These last studies elucidated the role played by instantaneous peaks in boundary shear stresses due to sweeps in initially entraining sand grains from stable bed positions, as well as the suspension of entrained sands "trapped" in ejected fluid parcels. Sumer and Oguz (1978) and Sumer and Deigaard (1981) carefully tracked the suspension trajectories of relatively heavy sand particles and found a close correspondence with the kinematics of burst motions. In the case of the heavier particles, a manifestation of the "crossing-trajectories effect" (Yudine, 1959) was in evidence: initial upward particle trajectories from the boundary were interrupted before the ejected eddies lost their identity, the particles in effect falling out of the ejected fluid parcels.

More recently, acoustic monitoring of "self-generated noise" due to gravel motion in a tidal boundary layer confirmed that inrush or "sweep"-like events were those responsible for most of the sediment transport when particles are too heavy to be suspended (Heathershaw and Thorne, 1985; Thorne et al., 1989). Use of fast response optical or dynamic suspended sediment sensors has similarly allowed Soulsby et al. (1984, 1985) and West and Oduyemi (1989) to begin the study of turbulent fluctuations in near-bed sediment concentration and the suspension effects of burst-like intermittent
motions in open channel flows. The latter particular issues will be central to the present study, as well.

1.3 Sedimentary bedforms and bursting

The tendency for sandy flow boundaries to develop into ripple or dune bedforms produces perturbations of the near-bed streamlines and thus modulation of local shearing conditions. In turn this modulation has the potential to affect local burst generation and sediment transport, and thus bedform evolution itself. A crucial link in this hypothetical feedback effect may be the sensitivity of local burst generation to downstream pressure gradients. There is evidence of enhanced bursting in adverse gradients (e.g.: Kline et al., 1967), while locally adverse pressure gradients are known to occur over much of the lee side of bedforms, where they often lead to flow separation (e.g.: Raudkivi, 1964; Buckles et al., 1984). Spatial modulation of bed surface pressures, as well as that of turbulence parameters such as Reynolds stresses, are well documented from laboratory experiments over artificial waviness introduced into flow boundaries (Kendal, 1970; Hsu and Kennedy, 1971; Zilker and Hanratty, 1979; Buckles et al., 1984).

Comparatively few detailed data are available on bursting-related sediment transport patterns along the surface of bedforms, however. Ikeda and Asaeda (1983) observed in the laboratory preferential burst-like activity and related sand suspension near the reattachment point on the lee side of ripples. A peak in the power spectrum of suspended concentration was used to confirm the outer flow scaling of burst recurrence, suggesting that the events near the reattachment point might be somewhat more periodic than the bursting reported near flat boundaries. High-speed movie camera observations by Itakura and Kishi (1980) of eddy motions over solidified sand dunes in the laboratory similarly revealed more intense bursting near the reattachment point.
Interestingly, these last researchers found that burst frequency near the reattachment point followed a Strouhal scaling in which the dune height replaced total boundary layer depth, the latter being the usual length scale in the outer flow scaling of bursts. Along with the indications of event periodicity mentioned earlier, this finding suggests that vortex shedding along separated shear layers in the lee of bedforms may also have been involved in these cases. The relation between such turbulent "events" over bedforms and "classic" flat boundary bursting remains to be investigated.

Consideration has also been given in the literature to possible links between burst mechanics and sedimentary instabilities leading to the development of bedforms. Ripples are thought to reflect instabilities in sediment transport in the streaky, viscous sublayer, involving grain pile-up and flow separation (Williams and Kemp, 1971; Yalin, 1972). As both dune wavelength and burst scales appear to depend on flow depth, a few authors have suggested a direct interaction between them (e.g.: Yalin, 1972; Jackson, 1976). Due to lack of data these last models, however interesting, are speculative and the details of the proposed interactions remain sketchy.

1.4 The objectives of this study.

1.4.1 General study definition

As explained above, this study will focus on the importance of burst-like motions in vertically suspending sands above an active river dune field. This issue is of fundamental interest to students of river mechanics: for example, establishing that distinct burst-like events of known recurrence were responsible
for the bulk of suspended sediment transport might, eventually, lead to improved parameterisations of sediment transport, as well as possibly shed light on bedform genesis. To the author's knowledge, no such study has been conducted to date in a large river at high flow. Particular difficulties in gathering the required data in such environments will be discussed in the next chapter. The object of this study is thus to analyse in detail relations between turbulent stress and sediment suspension "events" in a typical fluvial context. Given the technical difficulties encountered in data gathering, investigation of the effects on these relations of changing flow and bed conditions and sensing height, will be left to further studies.

Before introducing specific research questions and objectives, an outline of the type of data collected will be presented next. The key data for this study were provided by a fast response optical turbidity sensor, monitoring fluctuations in suspended sand levels, deployed at 1 m from the bed alongside a bidirectional electromagnetic flow meter sensing velocity components both streamwise (u) and normal to the boundary (v). Eddy correlation methods applied to these 3 signals will shed light on vertical fluxes through sensor level of both horizontal momentum (the Reynolds shear stress) and suspended sediment, and the uv quadrant method (e.g. Willmarth and Lu, 1974) will be used to detect burst-like motions. This type of data is akin to that recently gathered by Soulsby et al. (1984, 1985) and West and Oduyemi (1989), in a tidal (rather than fluvial) environment and, as will be seen in the next section, with somewhat different objectives.

Given the complexity of turbulent flow fields, the physical insights obtainable from Eulerian data on momentum and sediment fluxes at one point in the flow is of course limited. Sediment dispersal from the bed would be better described in a Lagrangian (flow parcel tracking) framework. Because of the severe problems of interference generated by multiple probes aligned to track events, it was thought that, at this exploratory stage, extended
observations at one point could nonetheless throw useful light on intermittent momentum exchange and suspension.

A number of factors were involved in the selection of a 1 m sensing height for this study. The latter corresponds to the general area of the flow where the greatest bed material (sand) flux occurs, with both sediment concentrations in suspension and downstream velocities simultaneously high. Indeed, under typical freshet conditions near Mission approximately half the total sand load of the 10 m deep Fraser River is transported within 2 m of the river bed (McLean and Church, 1986). However turbulent events control entrainment at the sedimentary bed itself (processes not directly observed in this study), the suspension mechanisms that have an influence at the 1 m level, and are studied here, have a strong bearing on downstream suspended sediment transport, and as such are worthy of attention in their own right. Other technical reasons for choosing the 1 m sensing height will be discussed in the next chapter.

A number of data sets were gathered in 1987 and 1988, in different fluvial and tidal environments within the Fraser Valley area. The data sets collected and deployment, sensor malfunction and data corruption problems encountered in these efforts will be summarised in the next chapter. The main findings reported in this study are based on the highest quality data set available, collected June 13, 1988 on the Fraser River near Mission, B.C., Canada; during this run all sensors functioned properly, flow conditions were reasonably steady, and signal corruption by water-borne organic debris was less persistent than in any of the other runs. These data were gathered over a 7 hour period above a field of mostly small dunes, 8-30 cm in amplitude, in a 10 m deep flow with a 1.4 m/s surface velocity. Further details on flow conditions and data gathering methodology will also be found in chapter 2. Because of the length of usable records gathered in the June 13 run near Mission, these data provide the best estimates of the statistics of flux intermittence and spectra under steady fluvial conditions that
could be obtained over the 2 field seasons. The June 13 results are nonetheless further substantiated in the thesis by more limited data sets gathered at other river sites and times.

1.4.2 Study outline and specific objectives.

As discussed in section 1.1, it has commonly been assumed that intermittent burst-like ($u'v'$) events in tidal flows are the signature, as they advect past the sensor location away from the bed, of 3D bursting structures similar to those observed in simpler laboratory flows. Two criteria have often been considered to be, in effect, diagnostic of turbulent bursting when analysing such records (e.g. Gordon, 1975; Anwar, 1981):

a) A high level of "intermittence" in the ($u'v'$) signal; that is, relatively brief record segments identified as intense "ejections" ($u'<0, v'>0$) and "inrushes" ($u'>0, v'<0$) dominate the overall $<u'v'>$ covariance.

b) Mean recurrence periods of intense ($u'v'$) events that appear to conform to the outer flow scaling (1) of laboratory bursting.

This "$u, v$ quadrant" method has been used almost exclusively to analyse records from difficult geophysical environments, because it does not require multi-point observations, very high-frequency sensor response or subjective frequency filtering procedures. The above two criteria will be applied to the ($u'v'$) records in the fluvial environment to determine whether burst-like events similar to those occasionally reported in benthic and tidal flows can be identified. It must be kept in mind however that the burst signature just described (based on ($u'v'$) records well away from the wall) has only been validated in studies of lower Reynolds number laboratory flows over flat boundaries (e.g. Lu and
Willmarth, 1973). In addition to involving subjectivity in counting "events" (cf. section 1.1), the above criteria may not be entirely sufficient or necessary to diagnose the presence of bursting motions in deeper/faster flows over complex boundary geometries. There, other mechanisms may produce "burst-like" u'v' events, or classic burst periodicity may not strictly apply. In the absence of fuller flow visualization data to seriously address these larger questions, the most that can be done in this study is to investigate whether burst-like (u'v') events conforming to the two above criteria occur in the study conditions.

1. A first objective of this study will thus be to investigate intermittent (u'v') "events" 1 m above river dunes in strong sediment transport conditions in the light of these two conventional criteria for bursting. Of interest here is whether (u'v') events in the study conditions conform to, or deviate from the classic properties of boundary layer bursting often assumed to apply in fluvial environments as well (e.g. Jackson, 1976; Allen, 1985). The study data cannot resolve the more fundamental question: how are these "events" in rivers fundamentally related to classic bursting?

This first objective will be pursued in chapter 3, devoted to momentum exchange. Chapter 2 deals with methodology.

The main aim of this study however is not to define more appropriate scaling for momentum exchange "events" in the fluvial environment, but rather to assess the importance to sediment suspension and transport of those large-scale momentum "events" that are present. This question will be pursued in chapter 4.

Whatever their ultimate relation to the classic bursting phenomenon (an issue that cannot be settled in this study), intense
(u'v') events are nonetheless interesting to the process geomorphologist in their own right. They reveal the occurrence of strong turbulent disturbances in the near-bed flow and these are likely to have implications for sediment entrainment and suspension. However, many fewer data are available on turbulent suspension events than on momentum exchange in natural channel flows.

Investigations to date have been conducted in tidal flows and have mostly focused on the variation of vertical sediment eddy diffusivity and fluxes with tidal phase. Soulsby et al. (1984, 1985) monitored horizontal suspended sand fluxes as well as horizontal and vertical flow fluctuations within 33 cm of the crest of a large sand wave in a tidal estuarine flow. West and Oduyemi (1989) report similar types of observations within 1.25 m of the bed in tidal channels from which they also derive information on frequency content of the suspension processes. These last authors also describe large intermittent contributions to the vertical suspended sediment flux in their near-bed records. Their analysis however failed to indicate to what extent these events corresponded to the intense stress bearing episodes, i.e. burst-like (u'v') events. Pursuit of this question is the second and principal objective of this study:

2. An analysis will be conducted of the "suspension efficiency" of strong stress-bearing "ejections" and "inrushes" (identified in (u'v') records), as well as the recurrence periodicity of dominant suspension events. In particular the following "natural" conjecture will be investigated: that those ejections contributing most to momentum exchange vertically through the sensor level (and studied in chapter 3) play a comparably large role in sediment suspension.
A range of issues will thus be addressed, based mainly on observations from one specific geophysical flow context. The underlying motivation for this study is to gain insight, using conventional analytical techniques, into the usefulness of the burst concept in understanding sediment suspension in a large-scale fluvial context.
CHAPTER 2

METHODOLOGY

This chapter will firstly discuss sensor deployment methods and sensor characteristics, high and low frequency losses, as well as ancillary apparatus used during data collection. Then, study site conditions will be presented as well as the quality of the various data sets collected during the 1987 and 1988 field seasons. Various procedures of preliminary data qualification and transformation will also be introduced. Finally some comments will be made on problems of data analysis specific to a field (as opposed to laboratory) study of this kind.

2.1 Sensor deployment methods.

The first problem to be solved in this study was that of deploying the flow and turbidity sensors, from a floating platform in a strong and deep river flow, so that they would lie stably in the desired position 1 m off the bed. In contrast to tidal deployments, in this study the sensors could not be lowered, oriented and well secured during nearly slack flows. As a consequence it was first necessary to design a sensor support frame that would self-align into the strong mean flow when approaching the bed and remain stable after touchdown, as well as a surface work platform that could handle the required loads. Over the first months of the study, a streamlined steel frame was conceived and tested that could deploy the turbidity and bidirectional flow sensors with the proper orientation into fairly unobstructed near-bed flow. A major constraint in doing so was to minimise the total weight and drag of the frame without compromising its stability; bed
disturbance near the frame had to be minimised and the frame had to
be deployed from a relatively light floating platform (for reasons
described below). Fig. 1 (top) shows the frame that was eventually
developed (without the sensors). The frame consists of a weighted
rounded base supporting a light superstructure made up of 3 sections
of steel pipe. The vertical front pipe is 2.5 cm in diameter and
serves as support for two steel arms projecting forward from the
pipe to hold the sensors in the flow. Fig. 1 (bottom) is a close-up
of the arrangement of the two main sensors on these support arms:
the bidirectional electromagnetic current meter on the left and the
Optical Backscatter Sensor (OBS) measuring suspensate reflections on
the right (the pipe intake behind the OBS head is part of the
suspended sediment sampling apparatus, described in the next
section). Once clamped onto the support arms, the sensors lie well
above and slightly upstream of the base of the frame. The sensor
support arms can also slide on the vertical front pipe to vary the
height of sensor deployment above the bed.

The two pipes rising vertically from the back of the frame
(Fig. 1) hold a pair of fins (interchangeable in size) that orient
the frame into the flow during deployment. The base of the frame
measures 1.25 m by 1.1 m, and stability of the frame on the bed is
assured by a total ballast of 90 kg of lead, half of which is cast
into the base while the other half is bolted on to adjust horizontal
trim. The total height of the frame is 1.2 m, and total weight with
sensors approximately 120 kg.

Except for the front pipe and sensors themselves, the main
drag producing elements are at the back of the frame, more than 1 m
downstream from the sensor location. The large gap between the
fins, as well as the use of smaller fins than those depicted in
Fig. 1 in the fast flows during the main data runs is expected to
have produced only minor disturbance of the mean streamlines at the
sensors. Any such disturbance was corrected by the coordinate
transformation of velocities described in section 2.5. Rapid
distortion effects on Reynolds shear stresses due to streamline
Fig. 1:

(top): Side view of the bare sensor support frame.
(bottom): Close-up of the two main sensors on the frame support arms: the bidirectional EM flow meter is on the left, the Optical Backscatter Sensor (OBS), on the right. The pipe intake behind the OBS unit is used to sample suspended sediments.
perturbation (e.g. Wyngaard et al., 1985) are also expected to have been small, given the limited high frequency response of the flow sensors (only large eddies are monitored) and the location of the sensors well upstream from the main sources of flow distortion.

The disturbance to advancing bedforms close to the base of the frame is harder to quantify. Disturbances to local bedform geometry near the frame have to be minimised since, if large enough, they could affect the velocity signals monitored at the sensors. As the main drag producing elements were high on the frame and its base itself was relatively unobtrusive as well as partially buried, the disturbance to dune-scale bedforms should, in any case, have been limited. Smaller and higher celerity bed "ripples" occupying the stoss sides of dunes, however, are more likely to have been disturbed as they arrived close to the frame base. The focus of the analysis, however, is on large turbulent eddy motions; these are convected by the strong mean flow to the sensor position and for the most part depend on shear conditions meters upstream from the frame. Such eddies are thus unlikely to be affected by small disturbances to bedforms near the base of the frame, lying 1 m vertically under the sensors.

This study was conceived as the first component in a longer term series of investigations of suspended sediment transport conditions in a variety of river environments. To allow for eventual deployment of this sensor frame in a range of stream environments (often remote and unsuitable to launching or maneuvering a large boat), major efforts were also dedicated at the start of the study to designing a strong, yet light weight and mobile, floating work platform. The platform was designed and constructed by the writer in collaboration with J. Skapski, Eng. Technician in the Department of Geography at U.B.C. It incorporates a cutout deck at the back, over which a DC powered winch is mounted on an A structure (Fig. 2), and an outboard engine set at front. The two 0.6 m diameter and 4 m long cylindrical hulls are constructed of fiberglass, and provide ample buoyancy to lift the frame from the bed unless the latter is badly
Fig. 2: Work platform used to deploy the submersible frame.
snagged on river bottom debris. The rest of the platform structure and decking is made up of bolted aluminum segments; these can be rapidly disassembled into a few components weighing each under 50 kg for transport, then reassembled at a remote river bank and launched without need for a boat ramp. A two person crew can, if necessary, transport the disassembled work platform on the roof of a small van to a remote river site and then carry the pieces through rough bush to stream bank for assembly.

Once the platform is motored and then anchored at the selected site, the frame and sensors are gradually lowered down through the opening at the back of the deck, drifting somewhat downstream in the process (Fig. 3). In all flow velocities encountered the stability of the frame when suspended just under the flow surface was excellent, with no tendency for yaw oscillation. Lowering of the frame to the river bed is interrupted for some moments when the frame lies a few decimeters above the bed, to assure that the frame axis is approximately aligned with the mean flow direction at the bed. The frame and sensors are then deposited onto the bed. The existence of appreciable multi-second turbulent fluctuations in the lateral velocity component implies that the frame orientation at touchdown may still deviate from the long-term mean flow azimuth by as much as 15 degrees; this factor could lead to, at most, a 4% uncertainty in the flux covariances involving the horizontal flow component (Pond, pers. comm., 1990). The precise orientation of flow sensor coordinates in the vertical plane is of much greater consequence: the procedures to align these with the mean shear flow are discussed in sections 2.2.1 and 2.5. After deployment and throughout data logging, a constant check is kept that the steel support cable remains loose and the signal cables free, thus assuring that the frame is not slowly dragging on the bottom. The possibility of fouling of the sensors was minimised by running the sensor cables towards a support loop at the back of the frame and then upward to the work platform.
Fig 3: Frame being lowered to the channel bed from the back of the floating platform. Note that smaller fins than shown here were used in the stronger flows on June 13, 1988, near Mission.
By varying the size and drag of the tail fins and the amount of lead ballast on the frame it was possible to eventually fully stabilise the frame in a range of deployment conditions. Occasionally deployments had to be interrupted, the frame lifted and relowered or data discarded if boat waves from river traffic exerted undue heave on the frame support cables. A more persistent and problematic source of data corruption was interference of suspended organic debris with the sensors; this important problem will be discussed in section 2.3.

2.2 Sensor characteristics and frequency losses

2.2.1 Electromagnetic current meter and high frequency losses.

Velocities were monitored with a Marsh McBirney (Inc) model 524 bidirectional electromagnetic (EM) current meter with 10 cm sensing sphere and 0.2 s time constant, adapted for 12 VDC power supply. Such sensors are quite commonly used in benthic and tidal boundary layer studies, for which they display reasonably good flow direction and frequency responses. The velocity channel that had the best noise and zero drift characteristics ("Y") was set to sense flow normal to the base of the frame (cf. Fig. 1, bottom), while the other ("X") sensed flow along the frame axis.

Because the fore-aft tilt of the frame depends on the local geometry of the bed at touchdown, there is no guarantee that in a given deployment the base of the frame parallels the local mean boundary orientation, and hence that velocities normal to the base (the Y component) in the long term average to zero. The good cosine (directional) response of the sensor to the two orthogonal flow components (as documented by Marsh McBirney Inc.) allows, however, the frame of reference of the velocity components to be rotated at
the data analysis stage, to compensate for this tilt of the frame. Thus the velocity component normal to the mean boundary \((v, \text{ with zero mean and defined as positive upwards})\), as well as the component in the downstream (mean streamline) direction \((u, \text{ positive downstream})\) can be retrieved. The importance of this data transformation will be discussed further in section 2.5. Its accuracy depends directly on the precision of zero flow readings on the EM flow meter. Still water output noise and zero drift were first tested in the laboratory in March 1987. Both channel outputs were monitored over 7 hours with the sensor on DC power immersed in a large pail of tap water on the UBC campus. Observed long term zero drift was under 0.5 cm/s, rms noise of X and Y channel outputs were of the order of 0.7 and 0.8 cm/s, respectively and zero offset trim potentiometers were adjusted to bring the mean output to zero. In June 1987 the still water output stability was further tested in the field in a large pail of Fraser River water from the study area near Barnston Island (then well upstream from the estuary salt-wedge; see Fig. 5): X and Y channel rms fluctuations based on two hours of monitoring were comparable to the laboratory results, at 0.9 and 1.0 cm/s, respectively and the mean drift against laboratory zero was under 0.6 cm/s. These tests indicate that the zero stability of the EM meter is good both in UBC tap and study condition freshwaters.

EM velocity meter calibrations were checked separately for each channel against a recently calibrated Ott type meter at river sites. Comparisons were done in 3 flow strengths (4 with the still water tests) by deploying side by side the Ott meter and carefully oriented EM meter and noting 4 minute average velocities. The results for both channels are presented in Fig. 4. The Ott calibration error in a towing tank is of the order of 0.3 cm/s. In turbulent flows with intensity below 0.2, such as in the study conditions, this error is estimated at under 1% (thus under 1.1 cm/s for all values in Fig. 4). The EM meter results of Fig. 4 suggest that sensor linearity is roughly within the manufacturers
Fig. 4: Calibration data for EM current meter. Reference velocities are based on 4 minute readings by Ott meter in river flows (+/- 1 cm/s).
specifications (2%). The EM output calibration constant for each channel was computed based on the data of Fig. 4.

Some of the factors determining the height above bed at which a flow sensor is to be deployed are its frequency response and the fraction of the high-frequency turbulent spectrum that needs to be recorded to satisfy the study objectives. This is because the fraction of the total turbulent energy above any given frequency tends to decrease away from the immediate boundary. The 0.2 s low-pass filter constant on the Marsh McBirney unit cuts off 98% of the power of velocity fluctuations at 5 Hz ($T=0.2$ s), half the power at approximately 0.8 Hz (1.25 s) and only 10% of the power at 0.25 Hz (4 s). Using the half-power figure as nominal cutoff frequency ($f=0.8$ Hz), this translates into a non-dimensional cutoff frequency $n=fz/U$ of 0.8-0.9 for sensors deployed at $z=1$ m from the boundary, where the mean velocity ($U$) in the main study runs was 0.8-0.9 m/s. Use of the similarity scaling frequency $n$, conventional in atmospheric surface layer studies, is also common in tidal boundary layer studies (e.g. Soulsby, 1977; Heathershaw, 1979; Anwar, 1981). This non-dimensional frequency can be interpreted as the ratio of sensor height to streamwise dimension of an eddy, assuming frozen turbulence behaviour.

Panofsky and Dutton (1984) state that $n$ values in the range 1 to 10 mark the upper limit of the energy containing range and the start of the inertial subrange in atmospheric surface layer turbulence. A nominal flow sensor high frequency cutoff (half-power) of 0.8-0.9 in this study would thus imply that all but the smallest "energetic eddies" should have been monitored. "Macroturbulent" eddies that are considered important in sediment suspension (e.g. Matthes, 1947) as well as bursting motions are generally taken to be included in the energy containing range. Soulsby (1980) states that a high-frequency cutoff of $n=1$ still excludes between 20 and 30% of the total variance of the vertical turbulent fluctuations in near-bed tidal flows, but only about 5% of the horizontal variance and the Reynolds shear stress covariance, which both are dominated by
larger eddies.

Had the velocity sensors been deployed much closer than 1 m to the boundary, a substantial fraction of the energy containing eddies (and potentially some of the bursting motions themselves) might have been filtered out due to the limited sensor response. The combination of a 1 m sensing height and 0.2 s flow response-constant is generally comparable to that used in previous bursting studies in benthic or fluvial boundary layers (e.g. Heathershaw, 1979; McLean and Smith, 1979).

In addition to the frequency response, such flow sensors also have a limited wavenumber response. Spatial averaging of velocity over the unit’s sensing volume, by smoothing out the response to smaller eddies, can become a limit when the bed is approached. Based on the manufacturer's specifications the 10 cm diameter sphere averages the flow in a 30 cm diameter volume and would thus significantly damp the response to eddies smaller than some 50 cm (see also discussion in Soulsby, 1980).

While the dynamic response of the current meter precluded observations much closer to the bed than 1 m, the maximum practical distance of deployment off the bed was determined by the difficulty of ensuring stability of a larger submersible frame. The 1 m sensing height is a compromise based on the exploratory nature of the research and the limits of available equipment and budgets. It also corresponds to the general area of the flow where the greatest suspended bed material (sand) transport tends to occur.

2.2.2 Optical Backscatter Sensor

To monitor suspended sediment fluctuations at a rate comparable to that provided by the velocity sensor, a fast response concentration sensor is required. Both dynamic impact (Soulsby et al., 1984) and optical sensors have been used (West and Oduyemi, 1989, and this study). Both types of sensors can produce very good linear calibrations of output against sediment concentration in
laboratory conditions, when in the presence of particles of uniform size (in the case of the dynamic Sand Transport Probe used by Soulsby et al. (1984), concurrent fast response measurements of velocity are also required). Unfortunately, calibration in the presence of variable sediment mixtures remains a problem with both sensor types. The sensitivity of the optical units peaks for silt-clay particles while, in the case of the dynamic STP unit this can be set to zero by varying response thresholds. However, even for the latter sensor, sensitivities to the different sand fractions are not constant, and field calibrations against total sand concentrations display substantial scatter (Soulsby et al., 1984). Further research is required to develop a truly accurate fast response sensor for suspended sand concentrations in the environment. Errors introduced in estimates of suspension fluxes and spectra through the use of the presently imperfect sensor calibrations remain poorly quantified at this stage.

In this study, the Optical Backscatter Sensor developed at the University of Washington (Downing et al., 1981) was used to monitor concentration fluctuations (cf. Fig. 1, bottom). It detects the intensity of back-reflection of infra-red light from the suspended particles in a small volume of flow passing by the sensor head. Because of the rapid attenuation of IR light in water the sensing volume is only of the order of a cm$^3$. Laboratory tests have shown that the response to increasing concentrations of a given sediment distribution is linear over a considerable range (e.g. up to 100 ppt for a medium sand; Downing et al, 1981). However, as noted above, the response coefficients vary with sediment size, shape, mineralogy etc., and calibration of the output to actual concentrations in the field environment is necessary. Apparatus to this end is discussed later in this section. Calibration tests (section 4.1) will show that, despite the high sensitivity to the silt/clay fractions, the response to the much larger fluctuations of sand concentration is clearly detected in the records produced by the OBS in the study conditions.
The inherently high dynamic response of the optics and electronics of the OBS as well as the small size of its sensing volume require that its output be low-passed filtered to match the dynamic response of the flow meter. The output was thus run through a low pass filter adjusted to a frequency cutoff similar to that of the velocity meter. This procedure was also important to introduce a phase lag at the higher frequencies of OBS output, to roughly match the lag introduced in velocity output by the latter's RC filter. Failure to do so would bias velocity-concentration covariances (sediment fluxes) at higher frequencies (mostly in the range f>0.5 Hz). Although the phase shift spectra of the velocity and OBS filters may not have been identical, the remaining bias is thought to be unimportant, as the higher frequencies will be seen to make a minor contribution to the covariances.

2.2.3 Other apparatus

A variable speed peristaltic pump on deck was connected to a 20 m long plastic pipe (1 cm internal diameter), with intake 30 cm behind the OBS sensing volume on the frame (cf. Fig. 2). Pipe output was at a sampling station on deck. This apparatus allowed physical sampling of suspended sediments at the sensor and a degree of calibration of the OBS output. The intake speed was adjusted to match the mean horizontal flow velocity at the time of sampling, to avoid biasing the sand content in the collected sample. The time of sampling was carefully synchronised (to 1 s accuracy) with the OBS record, allowance being made for the time of travel of the sample from OBS sensor to sampling station. Laboratory tests had demonstrated that sands travelled the length of the pipe at essentially the intake velocity (generally of the order of 0.8-0.9 m/s) and that sample travel time (to 1 s) could be predicted on the basis of this velocity and pipe length. Collected samples corresponded to 5 to 10 s of flow at the OBS sensor and calibration
was limited to corresponding mean values of the OBS record. The results of the calibration are presented in chapter 4.

A mostly unsuccessful attempt was made to document the passage of any bedforms underneath the sensors. A Raytheon DE719 echo sounding transducer (200 KHz acoustics) was mounted on the frame. The transducer was supported by an extension arm (not shown on Fig. 1) located somewhat upflow and 25 cm to the right of the OBS unit; thus the transducer pointed slightly upstream and near the right margin of the base of the frame. Event marks were made every minute on the chart recorder on deck, synchronised (with 1 s accuracy) with those on the velocity and turbidity records. Possibly due to disturbance of the smaller bedforms, as well as tilt of the sensor frame and consequent improper acoustic beam orientation, bed height oscillations could be detected only briefly and intermittently during most deployments. It was not generally possible to clearly relate these intermittent signals to known bedform scales present in the study conditions.

Velocity components and OBS output were sampled, digitised and stored on magnetic tape, along with statistical summaries, time and date marks, using a Campbell Scientific Inc. 21X data logger. A 5 Hz sampling rate was selected. This rate led to negligible aliasing; e.g. only 9% of the relatively small power present in velocity fluctuations at the cutoff frequency of 2.5 Hz, and 2 % at 5 Hz, pass the velocity meter’s low-pass filter. Power spectra presented later will show that the resultant velocity/turbidity power at the cutoff frequency is negligible compared to that at the lower frequencies in this study. Use of a faster sampling rate led to data overflow problems, given the minimum computing required to control the logging process.
2.2.4 Low frequency losses.

In this study the difficulties in assessing significant low-frequency contributions to the fluxes, within an achievable total record length, are greater than that posed by the better documented high-frequency instrument losses (section 2.2.1, above). A qualitative discussion of the importance of the low-frequency fluctuations to momentum and sediment fluxes will be presented in the last section of this chapter. Preliminary surveys indicated the presence in the velocity and OBS records of strong multi-minute fluctuations (many with periods over 10 minutes) in nominally steady river flows. Examples of these are given in section 2.5. This indicated that the longest records practicable should be collected in the study environment, to help resolve the role of these very low frequencies in momentum and sediment exchange. Possible generating mechanisms for such low-frequency flow cycles will be briefly considered in section 2.6.

In the presence of low-frequency fluctuations not usually important in benthic studies, the useful nomogram presented by Soulsby (1980, his Fig. 3) for low-frequency losses as a function of record length may be assumed to underestimate the low-frequency contributions to variances in this study. Long-term mean vertical sediment and momentum fluxes in such an environment may be extremely difficult to assess accurately. However, the complete evaluation of these integrated fluxes is not necessary to the elucidation of burst-scale vertical momentum and sediment mixing, the aim of this study.
2.3 Sensor output contamination by organic debris.

Serious and persistent data corruption in this environment results from the passage very close to, or contact with the sensors of large pieces of organic debris such as leaves and bark. Due to erosion of vegetated banks, such debris in general is an integral part of the material transported in traction and suspension by river flows. The presence of log booms along many large rivers in the lower Fraser Valley may have amplified this problem in the study environment. This type of data corruption typically produces brief, unusually large velocity or OBS signals; since this study itself focuses on extreme stress and suspension events, eliminating record segments corrupted by organic debris was crucial before the study objectives could be pursued. Fortunately a fairly characteristic signature allowed corrupted segments to be identified and deleted. Much of the total records collected over the various deployments had to be rejected because of frequent periods of intense corruption.

During data logging major corruption events were easily noticed, as they led to overrange values of either velocity or turbidity output lasting tens of seconds. In these cases logging was interrupted, the frame lifted off the bed, and if necessary the sensors brought to the surface for cleaning. Typically a leaf would be found draped onto the sensors. After removal and inspection, the frame would be redeployed on the channel bed. Briefer or more subtle corruption events were identified at the data qualification stage. In addition to momentary overrange or clearly unrealistic values of any signal, identification in the case of the velocity records was based on a recognizable signature for organic corruption. It had been noted, when the frame was close to the surface, that occasionally a leaf draped onto the velocity sensing sphere tended to oscillate with vortex shedding, alternatively touching X and Y flow electrodes. This characteristically produced large synchronous...
Oscillations of both velocity outputs that were strongly positively correlated. The entire velocity record was thus inspected by computing 2 minute velocity variances and covariances. Periods when corruption had occurred stood out clearly in this analysis, with exaggerated velocity variances along with negligible or positive covariances, instead of the negative values of u and v covariances typical of boundary layer turbulence. The corrupted 2 minute segments tended to cluster together and detailed scrutiny could pinpoint specific corruption events within them. Such periods were then deleted from the analysis.

Record segments deleted on the basis of the velocity signals usually included overrange OBS returns and were assumed to be also unreliable as records of suspension events. In the case of the OBS signals however, it can be expected that minute organic debris forming part of the normal fluvial suspended load may have also frequently affected the sensor output, but in a way that cannot be identified separately from the bulk sediment signature. The latter events simply contribute to the random error in calibrating OBS output to mineral sediment concentrations which is assessed in section 4.1. The quality of the calibration relations will indicate that, outside of the periods of intense organic corruption, the OBS signals essentially reflected the suspended sediment load.

2.4 Study sites and near-bed flow records.

Table 1 lists locations, dates and main problems encountered during deployments in 1987 and 1988 for this study. Prior to June 1988 when the OBS unit became available, turbidity sensing was accomplished with an older optical transmissometer unit which was eventually found to be unreliable in the field. Deployments that
## TABLE 1

**FRASER RIVER DATA SETS**

<table>
<thead>
<tr>
<th>SITE</th>
<th>DATE</th>
<th>D(m)</th>
<th>V₁m(m/s)</th>
<th>Vₛ(m/s)</th>
<th>T (hr)</th>
<th>REMARKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>BARNSTON ISLAND</td>
<td>07.14.87*</td>
<td>9</td>
<td>0.85</td>
<td>1.3</td>
<td>3</td>
<td>transmissometer malfunction; much organic corrosion</td>
</tr>
<tr>
<td></td>
<td>07.15.87</td>
<td>7</td>
<td>0.75</td>
<td>1.1</td>
<td>2.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>07.16.87</td>
<td>5</td>
<td>0.6</td>
<td>0.8</td>
<td>3.5</td>
<td>&quot; &quot;</td>
</tr>
<tr>
<td>MISSION</td>
<td>06.08.88*</td>
<td>8</td>
<td>0.85</td>
<td>1.1</td>
<td>5.1</td>
<td>frequent boat traffic; organ.corrupt</td>
</tr>
<tr>
<td></td>
<td>06.13.88*</td>
<td>10</td>
<td>0.9</td>
<td>1.4</td>
<td>7.0</td>
<td>&quot; &quot;</td>
</tr>
</tbody>
</table>

D: local depth  
V₁m: velocity at 1 m off bed  
Vₛ: surface vel.  
T: total duration of deployments

*: results presented in this study
produced results of sufficient quality to be reported in this study are marked by asterisks in Table 1. Fig. 5 locates the various study sites discussed. In addition to the June 13, 1988 data from the Fraser River near Mission, which provide the main evidence discussed in this thesis, more restricted results from deployments on June 8, 1988 near Mission and on July 14, 1987, near Barnston Island are presented in the next chapters to confirm the main findings. As discussed in section 2.3, signal corruption by organics marred most of the deployments, and only brief record segments could be used in the final analysis.

Not listed in Table 1 are 5 deployments conducted between March and May 1988 in strongly tidal conditions on the lower Pitt River near the junction with the Fraser R. These tidal surveys were directed at clarifying the onset of suspension in gradually increasing flow conditions, a secondary objective not discussed in this study. Unfortunately the Pitt River study was not successful because of very intense signal corruption by organic debris as well as unreliability of the turbidity sensors used at the time.

The following discussion presents details on the study environments, with main emphasis on the key deployments near Mission. This site lies in a channel of the Fraser River to the south of Matsqui Island, in the Lower Mainland of British Columbia, Canada (Fig. 5, see blow-up map). The Fraser basin (area 228,000 km² at Mission) drains a large part of the interior and the Coast Mountains of British Columbia. Mean annual discharge at Mission is 3410 m³/s. The fairly straight and uniform reach of the river where the sensors were deployed is located 5 km downstream of Mission, and 2 km downstream of a moderately sharp bend on the channel. The channel cross-section is approximately trapezoidal over this reach, with a width of 250-280 m and depths ranging from 9 to 11 m during the survey period. Bed materials are fairly uniform medium sands (D₅₀=0.38 mm near Mission). Approximately 7 km upstream of Mission lies the zone where sand succeeds to gravel on the bed of the Fraser River. Further upstream there is an anastomosed-"wandering" gravel
Fig. 5: The study sites (*). Fraser River at Matsqui Island, near Mission (main site), and secondary site at Barnston Island, B.C., Canada.
reach of the river, which extends to the head of the Fraser Valley lowlands.

The main study data at Mission were collected during a period of snowmelt-fed high runoff on June 13, 1988. The discharge at Mission was 6500 m$^3$/s and had been gradually increasing over the previous week. Such a discharge is exceeded on average 13% of the time at the site. Surface velocities at the June 13 deployment station 80 m from the right bank, in 10 m depths, were 1.4 m/s and mean velocities over the vertical 1.1 m/s. The flow Reynolds number (based on flow depth) in the study reach was about 8 X 10$^6$; this is approximately 2 orders of magnitude higher than most of the values encountered in laboratory studies of bursting events. Bedforms in the study channel during this period generally consisted of small dunes (8-12 cm scale amplitudes) overriding larger ones (30-150 cm amplitudes). Fig. 6 presents a surface profile of bedforms in the immediate vicinity of the sensors during the June 13 deployment. The decimeter scale forms have wavelengths in the range 1.5-2 m, the larger dunes have lengths of 5-11 m. Smaller scale ripples (15-30 cm lengths), possibly also present would probably not have been resolved from the surface in 10 m depths.

During the June 13 deployment mean suspended sediment concentrations at sensor level were 500 mg/l. The decreasing concentration of suspended sediment (and resultant flow density) away from the bed produced a very weak degree of stable density stratification in the flow 1 m over the bed. The degree of this stability is estimated to have corresponded to a flux Richardson number $R_f$ of 0.02 in the June 13 conditions, based on a mean upward sediment exchange due to turbulent mixing of 3 g/m$^2$ s (estimated in section 4.4), a kinematic Reynolds stress of -28 x 10$^{-4}$ m$^2$/s$^2$ (cf section 3.1) and a mean vertical velocity gradient of 0.22 m/s/m, all at sensor height. Heathershaw (1979) considers that turbulence is completely suppressed at Richardson numbers of 0.25, while values less than 0.03 would represent essentially neutral conditions (no measurable damping of turbulence due to the stratification being
Fig. 6: A 160 m long streamwise bed profile showing dune bedforms taken on June 13, 1988 in the area where the sensors were deployed, southern channel of the Fraser River, near Mission.
discernable). The latter appears to apply to the study conditions.

The flow conditions at Mission were only approximately steady during the extended period of data logging on June 13, 1988 (7 hours, from 13:30 to 20:30 hrs, Pacific Standard Time). Fig. 7 presents a record of stage height (relative to an arbitrary datum) at the Mission gauge for a 3 day period including the 7 hours of data gathering (Water Survey of Canada, 1988, pers. com.). A 12 hour cycle in stage, of peak amplitude 15 cm (1.5% of depth at the study site), is the backwater effect of the tidal cycle at the mouth of the Fraser River in the Strait of Georgia, 85 river km downstream. The tides on the Strait were almost diurnal on these days, with one deep (4 m range) and a second very shallow cycle (0.5 m range). These are closely mimicked in the stage at Mission, where they occurred with a delay of some 4 hours.

These damped fluctuations were superimposed on a trend of increasing stage, of the order of 8 cm/day, reflecting gradually rising tributary inflow due to snowmelt in the mountainous Fraser R. basin. Over the total of 7 hours of data logging on June 13, this trend reflects a 0.6% increase in discharge at Mission. In the author's experience, a 1-2% fluctuation in flow depth during one daylight period is, in practice, close to the limit of flow steadiness that can be expected even in large natural streams. The effects of such slight non-steadiness in overall flow conditions on near-bed velocities at the study site will be discussed later in this chapter. Only minor corruption events were detected, and no redeployment took place, during a continuous 2.7 hr period starting at 17:00 hrs on June 13. The detailed analysis in the subsequent chapters is largely based on this segment of the record.
Fig. 7: Stage record at the Mission gauge of Water Survey of Canada, June 12 to 14, 1988. The study period on June 13 lies between the vertical lines. Linear trend indicated by dashed line.
The June 8 deployment near Mission (Table 1) occurred in only slightly weaker overall discharge conditions, somewhat upstream and across the channel from the June 13 deployments and in shallower flow. Hydraulic conditions were less intense: local depth was 8 m, surface velocities averaged 1.1 m/s and the bed near the sensor was mainly covered with 5-10 m length, 0.3 m height dunes. The June 8 deployment was marred by frequent interruptions due to boat traffic and persistent organic corruption of records. Analysis of 35 minutes of good quality OBS, u and v data (19:22 to 19:57 h PST) will be reported in coming chapters.

The surveys of July 1987 (Table 1) were also conducted on the Fraser River, approximately 40 km downstream from the Mission site in the southern channel at Barnston Island (cf Fig. 5). Deployments occurred at different stations in the reach in hydraulic and sediment transport conditions broadly comparable to those during the Mission deployments (5-10 m depths, 0.9-1.2 m/s surface velocities, dune bedforms). Optical transmissometer problems prevented extracting precise results on sediment transport events. Analysis of 57 minutes of uncorrupted u, v data (July 14, 1987, 12:30-13:27 h PST) for stress intermittence will be presented in chapter 3 along with the main 1988 results from Mission on that subject.

2.5 From frame based to boundary layer based velocity coordinates.

No tiltmeter data were available to monitor frame motions on the channel bed, although the weight of the frame made such motion unlikely. It was important however to verify whether shifts in the velocity coordinate system caused by any occasional motions of the frame might have produced spurious fluctuations in the records of near-bed flow. To establish that recorded velocity
fluctuations were genuine, and not the result of any frame rocking, total flow speed and angle (the latter positive upward relative to frame base) were plotted, instead of the separate X and Y flow components in the frame system of reference. While flow angle series may be affected by frame rotation, speed (the resultant of the X and Y flow components) as well of course as OBS return are invariant to rotations of the frame of reference.

Fig. 8 presents the entire 7 hours of flow speed, angle and turbidity (OBS) records for June 13, 1988, heavily smoothed with a 5 minute running mean, and disclosing long period fluctuations in these signals. As pointed out above, the strong fluctuations in speed and OBS output cannot be explained by frame rotation. Fig. 9 is a similar plot for an 80 minute excerpt from the record of Fig. 8, this time smoothed with a 40 s running mean and thus displaying strong higher frequency fluctuations, that again cannot be due to frame rocking. Some obvious relations among these signals will be discussed in the next section. All velocity fluctuations discussed in this study, including those at even higher frequencies (0.05 Hz<\(f\)<2.5 Hz) that have been largely filtered out from Figs. 8 and 9, similarly involved both speed and angle changes and thus could not have been produced by frame rotation. It is concluded that frame motions, if present, did not affect the flow series in a significant way.

The system of coordinates relating to the frame base used above is not suitable to computations of vertical momentum and sediment fluxes. The orientation of the frame-based X and Y velocity coordinates discussed in section 2.2.1 depends on the bed slope in the immediate area on which deployment happens to be established. They are thus of little relevance, in themselves, to understanding the flow. In particular, any time that the frame was lifted off the bed and redeployed the existing frame coordinate system was lost and a somewhat different one established. The natural coordinate system for vertical exchange of momentum and sediment from near-bed to the outer parts of the flow is one in which \(u\), the downstream flow
Fig. 8: 7 hour-long time series of flow speed, angle and OBS output 1 m above the channel bed on June 13, 1988, near Mission. The data have been heavily smoothed with a 5 min running mean. The flow angle is measured vertically from the multi-hour mean streamline orientation. Positive angles are upward.
period, to reveal higher frequency oscillations, smoothed with a 40 s running mean and covering a 1.3 hr period. 9: The same flow variables as in Fig. 7, this time for 1950–2050 hrs. OBS OUTPUT (mv)

FLOW SPEED (cm/s)

FLOW ANGLE (deg from horiz.)

OBS OUTPUT (mv)

Time (hrs, PST)
component, is parallel with the local mean boundary (itself perturbed by the large scale roughness of moving bedforms) and \( v \) is the component normal to the mean boundary. Turbulent Reynolds shear stresses, in particular, are known to be very sensitive to the proper orientation of the flow coordinates relative to the mean shear within a boundary layer (e.g. Pond, 1968; Kaimal and Haugen, 1969). Improper orientation produces contamination of the \( v' \) flow component by \( u' \), and hence the \( (u'v') \) covariance (or kinematic stress) by the strong \( (u')^2 \) term. Appreciable misalignment can also introduce spurious \( (u'v') \) events and affect the analysis of event recurrence. It can be estimated that an instability of \( (+/-) 1 \) cm/s in sensor zero (approximating the performance of the study unit as discussed in section 2.2.1) will lead to a 0.6 degree uncertainty in flow coordinates, and hence a 8% uncertainty in the \( (u'v') \) covariance (Pond, 1990, person. comm.).

In practice, the mean shear coordinates were approximated by rotating the raw, frame-based \( X \) and \( Y \) velocity components to compensate for frame tilt, to yield \( u \) and \( v \) values such that the long-term mean vertical velocity \( v \) during any deployment period is zero. The coordinate rotation is given by:

\[
\begin{align*}
  u &= X \cos \theta + Y \sin \theta \\
  v &= Y \cos \theta - X \sin \theta
\end{align*}
\]

The rotation angle \( \theta \) can compensate for the tilt of the frame in a given deployment; it was generally less than 3 degrees in our studies. It must be noted that this common, and generally unavoidable procedure for defining "internally" the boundary layer coordinates, based on the observed flow data itself, has drawbacks. Among others, it leaves the observer unaware of any mixing across the layer caused by the presence of "secondary" cells in the mean flow. Sets of weak, streamwise roll vortices, superimposed on the much stronger primary flow, have been documented in some channels. In the presence of such cells, mean shear coordinates defined at 1 m
from the bed, as above, may locally diverge from the "true mean boundary", towards or away from it depending on which side of a cell the sensors might be located. Assuming the cells were fixed relative to the sensor location during all of a deployment, only the turbulent vertical momentum and sediment mixing fluxes across the local mean flow coordinates would be computed. However it is precisely the turbulent mixing that is of primary interest in this study. Further problems of definition and statistical variability of Reynolds stress estimates based on this approach will be discussed in chapter 3.

2.6 Low frequency flow oscillations in rivers

The importance of low-frequency components in the data has already been seen in the filtered records presented above. Figs. 8 and 9 documented the existence of strong fluctuations of flow speed, angle and turbidity with periods of many minutes to hours at the Mission study site. There is in particular a multi-hour fluctuation in the June 13, 1988 records, with a peak in speed corresponding to a trough in angle around 17.5 hrs (Fig. 8). This long cycle at 1 m from the bed may have been caused by the slight tidal backwater cycle (of stage amplitude less than 2% of local depth) documented in Fig. 7. However, the delay of near-bed flow deceleration a full 2 hours beyond the start of tidal stage rise at Mission, as well as the coincidence of flow angle and speed changes suggests that the slight tidal effects may have been overshadowed by a multi-hour cycle possibly related to the advance of some large bedform.

The filtered records (Figs. 8, 9) also suggest the existence of approximately 20 minute period flow fluctuations, most noticeably in the speed record of Fig. 8 after 17.0 hrs, when the cycles have peak to peak amplitudes of as much as 15 cm/s. The same
"20 min" cycles are still visible in the less filtered speed record of Fig. 9. The existence of approximately 3 to 5 minute-period cycles "on the backs" of the 20 minute ones can also be detected in Fig. 9, most clearly in the speed record before 18.5 hrs. Similar multi-minute flow speed and angle fluctuations were detected at all study sites. Although the filtering of records that led to Figs 8 and 9 cannot in itself introduce low-frequency variability where none exists, it may have artificially enhanced the relative importance of these long period oscillations. The relative weight of these multi-minute oscillations will be estimated spectrally in chapter 3.

The nature of these particular fluctuations is of more than peripheral interest to this study. Slow turbulent flow oscillations for the most part do not figure in present conceptual models of alluvial sediment transport mechanics. The records presented in Figs. 8 and 9 suggest however that the multi-minute fluctuations are significantly involved in vertical momentum and sediment fluxes through the sensor level. A strong tendency for the flow to veer upwards (angle increases) as it slows down (speed decreases) is indeed noticeable in the records. As the flow angles are small, the horizontal component essentially dominates the total speed and so the observed pattern is for smaller downstream velocities to coincide with more upward flow, and vice-versa.

At the same time, higher turbidity levels are also associated with the slower and more upward directed flow, and lower turbidity levels with downward flow, most noticeably in the 2-5 min cycles in Fig. 9. This, for now apparent, statistical association of more upward directed flow with a deficit in horizontal momentum, as well as with higher sediment contents (and vice-versa) in low-frequency cycles will be quantified in coming chapters. It suggests that the process(es) responsible for these low-frequency fluctuations in fact also contribute to both sediment and horizontal momentum transport, vertically through the sensor level.

Multi-minute cycles in flow speed have been reported
previously in other rivers (e.g. Tiffany, 1963; Ishihara and Yokosi, 1967), but with little insight into their origin and significance. Ishihara and Yokosi (1967) suggest that such multi-minute fluctuations simply reflect large-scale turbulence. The issue of whether "turbulence" can explain such low-frequency oscillations in the Fraser River, or whether other process(es) might be also involved, is a complex one that cannot be completely resolved on the basis of the one point study data. A phenomenological approach will consist in comparing the u, v and uv spectra from the Fraser records with typical turbulent spectra in geophysical flows. The conclusions of this analysis will be presented in the next section (s. 3.1).

A few general comments on the origin of low-frequency river flow oscillations can be made here. If one understands the concept of turbulent eddy in its usual sense, as an evolving 3D flow disturbance convected with the mean flow, the often made hypothesis of fluvial "turbulence" at multi-minute scales has troublesome implications that should be noted. The hypothesis of Ishihara and Yokosi (1967) would imply advection past the sensors (at e.g. 1 m/s mean flow speeds) of highly two dimensional eddies, measuring many hundreds of meters in length (to produce multi-minute periods). The size of energetic turbulent eddies is known however to scale with the dimensions of the mean shear layer (i.e. the thickness of the boundary layer) from which they extract their energy. In river flows, they should scale with channel depth. The above authors did not suggest an energy generating mechanism for many hundreds of m long "two-dimensional" eddies, travelling contained within 1-10 m deep boundary layers between the river bed and the flow surface. This simple "frozen turbulence" interpretation may not be appropriate to describe such slow oscillations. It will be seen that less extreme interpretations are possible.

Different generating mechanisms for multi-minute near-bed flow cycles in rivers can also be suggested, although lack of data will prevent pursuing the issue further in this thesis. Fluctuations in time series of flow at only one point can be
visualised in different ways, in a spatial sense. Rather than being produced by extremely elongated turbulent eddies travelling at bulk flow velocity, it is also possible to interpret the multi-minute speed and angle fluctuations in the Fraser records (Figs. 8, 9) as slow fluctuations of the mean flow streamline at the sensor position (schematised in Fig. 10), over which faster turbulent motions are superimposed. Note in Fig. 10 the association between faster and downward directed flow (and vice-versa) seen in Figs. 8, 9. Note also that streamline curvature in this schematic is quite exaggerated; while multi-minute fluctuations in mean speed in the study records are important (of the order of 10 cm/s), hypothesized streamline angle oscillations would be very subdued, of the order of 1-3 degrees over periods of minutes (Figs. 8, 9).

What processes might produce gentle multi-minute streamline fluctuations at a given position in the flow? One process was alluded to in section 2.5. Large, streamwise vortices may be present in the "mean flow", and if their amplitude or location relative to the fixed sensor were to shift, for example in response to slowly changing bed conditions, slow changes in the mean flow at the sensor would be recorded. A more direct link with changing bed conditions is also possible. Bedforms advance during active sediment transport conditions, and some passages of faster, smaller bedforms under a fixed sensor frame can be expected during multi-hour records. In principle such passages directly produce, through pressure effects, local perturbations of flow streamlines (which may or may not be easily perceptible at sensor level, 1 m off the bed). Could this obvious source of streamline perturbation underlie some of the observed multi-minute (1-3 deg amplitude) flow oscillations?

Lack of data on small scale bed activity near the sensor frame prevented investigating this hypothesis in the study environments. For this speculation to be plausible, faster advancing, low amplitude bedforms (for example, 8-15 cm height, 1-2 m length "dunes" known to be present in the June 13, 1988 conditions, Fig. 6, or yet even smaller ripples) would have had to
Fig. 10: Schematic diagram of multi-minute streamline oscillations, with time, at sensor level in the study conditions. Angular deviations are much exaggerated. At any instant, turbulent flow parcels arrive at sensors from a range of directions spread around this mean streamline.
pass under the sensors as often as every few minutes (or as
infrequently as every 20 min, Fig. 8). This could imply bedform
celerities of the order of a few mm/s if, for example, passage of
the smaller length dunes present on June 13, 1988 near Mission were
to cause streamline perturbations of 3-5 min period (as in Fig. 9).

It is unclear whether such bedform celerities are possible.
There are unfortunately few data available on celerities of very
small bedforms in such fast, and deep flows, where these small forms
advance over the backs of the larger, easier tracked dunes.
Available laboratory data on celerities of small bedforms may not be
easily extrapolated to conditions in deep flows with multiple scales
of bedforms and considerable spatial variation in bed stress.

Since very little specifically is known about the movement of
small bedforms in deep flows and that some disturbance to these
forms is expected near the base of the sensor frame, a detailed and
unambiguous (almost visual) record of the nature of the bed activity
would be required to convincingly establish the link between
bedforms and multi-minute streamline perturbations at 1 m. Possibly
because of sonar beam tilt, the depth sounder mounted on the sensor
frame in this study failed to disclose unambiguous information on
bedform passage events (cf. section 2.2.3). In any case such depth
sounder records (even at two points) cannot directly disclose the
nature, form and length (and hence celerity) of individual bed
disturbances near the frame, crucial information to solidly confirm
the hypothesis linking streamline oscillations to bedform passages.
High suspended sediment concentrations near the bed make video
monitoring virtually impossible. A compact side-scan sonar
transducer with high spatial resolution would probably need to be
developed to allow detailed documentation of small-scale bedform
activity near such a frame, and its relation to long flow cycles.

In coming chapters, estimates will also be made of the
importance of these multi-minute flow oscillations to momentum and
sediment fluxes, before they are filtered out to leave the burst-
scale turbulent motions of main interest to this study.
CHAPTER 3  MOMENTUM FLUXES AND TURBULENT BURSTING EVENTS

The simultaneous time series of horizontal and vertical velocity fluctuations 1 m off the channel bed provide a means of estimating, through "eddy correlation" statistics, the rate of exchange of horizontal momentum (the Reynolds shear stress) through that height in the water column. In this chapter, the spectral contributions to momentum exchange will first be discussed. Then, objective 1 (cf. section 1.4.2) will be pursued: to describe "burst-like" stress events in a fluvial environment during high flows and contrast them to those reported in other geophysical flows. The role and timing of large intermittent contributions to momentum exchange will be analysed, and their possible relation to the "bursting" events identified in laboratory flows will be discussed. In the next chapter, the key objective of this study is pursued: an analysis is conducted of the effectiveness of the intermittent burst-like events in terms of sediment suspension.

3.1 The frequency distribution of momentum exchange.

Here the usual convention for fluctuations is followed:

\[ u' = u - <u> \]
\[ v' = v - <v> \]

where \( <> \) denotes a long-term mean, and \( <v> = 0 \). Inspection of simultaneous \( u \) and \( v \) records discloses that momentum exchange processes occur over a wide range of frequencies. Qualitative evidence was presented in the previous chapter of a negative
correlation between multi-minute period fluctuations of the vertical \( (v') \) and downstream \( (u') \) velocity components (see Figs. 8, 9). As discussed in section 2.6, these very low frequency flow fluctuations at the sensor tend to associate faster \( (u'>0) \) with downward \( (v'<0) \) flow, while slower flow tends to be directed away from the bed. On average such motions would produce a vertical exchange of horizontal momentum through the sensor height; specifically a retarding stress on the outer flow. Although low-frequency processes are not of central interest to this study, their importance to momentum exchange in the study conditions will be assessed as an element of general interest.

A stress bearing association of \( u \) and \( v \) fluctuations is also detectable in the faster turbulent components, superimposed on these multi-minute oscillations. This can be seen in Fig. 11, which shows 10 minute long time series, starting at 16:57 hrs PST on June 13, 1988, of OBS output along with \( v \) and \( u \) flow components. To extend the time base of the plot, minor fluctuations with periods less than some 2 s have been filtered out, using a 0.8 s running mean. Fig. 11 can be viewed as the last stage of a "magnification" of the records begun with Figs. 8 and 9; on it can be readily observed faster (multi-second-scale) turbulent motions, superimposed on the multi-minute velocity fluctuations. Notice that the 2 to 5 min "cycles" are strong enough to remain conspicuous in these largely unfiltered records, especially in the \( u \) and OBS series, despite the presence of the strong shorter period turbulent fluctuations. The tendency of upwelling motions \( (v'>0) \) to mostly bring relatively slower near-bed water parcels into the faster flow above sensor level, and vice-versa, can be detected over the full range of frequency components seen in Fig. 11, including the multi-second scale turbulence.

Spectral techniques will help in quantifying the relative contribution to overall momentum exchange of the various frequencies of flow fluctuations discussed above. An issue raised earlier (section 2.6) will be considered in this light: are the multi-minute flow cycles near the bed of the Fraser River unusually intense to
Fig. 11: A 10 min time series of U and V flow components as well as OBS output, revealing seconds-scale turbulent fluctuations superimposed on multi-minute flow oscillations. June 13, 1988 deployment near Mission.
represent simple boundary layer turbulence. Before presenting the
cospectrum of momentum exchange through the sensor level, individual
u and v power spectra will also be introduced and briefly compared
to those encountered in other geophysical boundary layer flows.

3.1.1 U and V spectra.

In practice spectral estimates based on a given record can
analyse the whole underlying process only if a large number of the
lowest frequency cycles involved are included in the record, to
average out their properties. The approach taken here was to analyse
only the low-frequency cycles with periods under approx. 14 minutes,
of which there was a reasonable number in the uncorrupted records of
June 13, 1988 near Mission. Spectral estimates of longer period
oscillations would have been marred by unacceptable sampling error.
Less well resolved spectra from another deployment will also be
presented that broadly corroborate the June 13, 1988 findings.

Individual 13.65 minute time segments (2^{12} data points
sampled at 5 Hz) were identified in the June 13, 1988 records during
which no apparent corruption of either velocity record by organic
debris could be recognised. In total, 2.7 hours of data were thus
retained, recorded between 16:57 and 20:00 hr. The variances of
horizontal and vertical flow components (3.3 minute averages) were
trendless during this period, despite a slowly rising stage at
Mission (about 2 cm/hr) due to tidal backwater; this weak
stationarity in the records is the usual requirement for spectral
decomposition.

To reduce the random error in the spectral estimates as
much as possible within this limited record length, 23 such 2^{12}
point time segments were delimited, allowing for 50% overlapping of
segments where possible (Bendat and Piersol, 1986). Each of these
segments was detrended by linear regression, tapered with a Hanning
type window, and fast-Fourier transformed. Thus, contamination of
the spectra by cycles longer than 13.65 minutes was inhibited. Power
spectral density estimates from the 23 records were then averaged, and further bin averaging of adjacent frequency bands was done where desirable to reduce the random variance of the estimates.

Even in laboratory flows, under the most steady conditions practically realisable, turbulent velocity spectra often show the greatest power density (per Hz unit of frequency) at the lowest frequencies studied (I. Gartshore, pers. comm, January 1987). There is typically however a frequency at which peak power per frequency decade occurs and this value provides a useful scale for the turbulence (Panofsky and Dutton, 1984). This peak is displayed in the standard area-preserving form of the spectrum, in which \((f \times \text{spectral density})\) is plotted against the log of frequency. Because of record length limitations, the peak may or may not be reached in observed \(u\) spectra. "Internal" adjustment of mean \(v\) to zero (section 2.5) will always produce a peak in the \(v\) spectrum. Fig. 12 contrasts these forms of the horizontal and vertical spectra for the June 13, 1988 data, smoothed by averaging 10 adjacent estimates. The OBS output spectrum for this run is also superimposed on the velocity spectra for later reference (section 4.2.1).

Soulsby (1977) documented the usefulness of scaling eddy wavenumber by sensor height (as a first approximation until further work defines other scaling length(s) reflecting complex bedform geometries) to compare among them benthic and tidal turbulence spectra, as well as atmospheric surface layer spectra. This scaling is implicit in the commonly used non-dimensional frequency

\[ n = f \times \frac{z}{U}, \]

where \(f\) is frequency in Hz, \(z\) is sensor height in m and \(U\) is local flow velocity in m/s. In the June 13, Mission data the non-dimensional and dimensional frequencies are approximately numerically equal, when the latter is expressed in Hz:

\[ n = \left(f \frac{z}{U}\right) \approx f \]

as the sensor height \(z\) was 1 m, where the mean flow velocity \(U\) was 0.9 m/s.
Fig. 12: U, V and OBS output power spectra in area preserving form. June 13, 1988 deployment near Mission.
Figs 13 and 14 compare the U and V spectra obtained on June 13, 1988 near Mission to those extracted from 57 minutes of data collected in slightly weaker flow conditions near Barnston Island (cf. section 2.4) on July 14, 1987, (in 9 m depths and with velocities of 0.85 m/s at 1 m from the bed). The scaling factor to non-dimensionalise frequencies \((z/U)\) was approximately the same for both records, and again \(f\) (in Hz) can be essentially taken as \(n\) on these plots. Because of shorter available records, the Barnston spectra have more sampling variability. Despite somewhat weaker U, V turbulent intensities in the Barnston flow, the shape of the spectra appear to be broadly similar to those near Mission.

Turbulence statistics are notoriously variable and the generality of conclusions that can be drawn here is severely limited by the small number of available spectra, a consequence of the dearth of uncorrupted data runs in the Fraser deployments. The location of the u, v spectral peaks in the Fraser data will nonetheless be compared with those of better documented atmospheric surface layer turbulence under similar conditions of near neutral (slightly stable) density stratification (cf. section 2.4). Panofsky and Dutton (1984) summarise some early atmospheric results in their engineering textbook (relying strongly on J.C. Kaimal's work). They report that for purely mechanical turbulence in the atmosphere (neutral stability conditions) the peak in the vertical velocity spectrum appears to occur at a non-dimensional frequency \(n=0.5\), i.e. for eddies as large as twice the sensing height. The variability in turbulent spectra however is considerable. Pond et al. (1971) for example present surface layer v spectra based on numerous records over the ocean in only slightly unstable conditions that tend to peak nearer \(n = 0.2\). Peaks around \(n=0.2-0.3\) were also obtained by Anderson and Verma (1985) and Smith and Chandler (1987) in atmospheric surface layer flows over, respectively, field crops and the ocean, under near-neutral conditions.
Fig. 13: U power spectra, superimposed, for main June 13, 1988 deployment near Mission and July 14, 1987 deployment at Barnston Island. See section 2.4 for flow conditions.
Fig. 14: V power spectra, superimposed, for main June 13, 1988 deployment near Mission and July 14, 1987 deployment at Barnston Island. See section 2.4 for flow conditions.
The peaks in the Fraser vertical spectra in Fig. 14 are centered around \( n = 0.1 \). However, the location of the peak in these spectra is somewhat affected by damping of faster flow oscillations due to the relatively slow frequency response of the electromagnetic flowmeter. As discussed in Chapter 2, the 0.2 s time constant has led to a 30% power loss by \( f = 0.5 \) Hz (\( n = 0.5 \)) for both components, so that most of the inertial range (at approx \( n>3-10 \), Panofsky and Dutton, 1984) and a small fraction of the faster energy-bearing components were not recorded. This accelerated roll-off somewhat shifts the vertical peak to a lower frequency. Compensating for frequency response one obtains a peak around \( n = 0.3 \). This is within the range reported above for \( v \) component turbulence in the near-neutral atmosphere.

Less constrained by proximity to the boundary, the horizontal eddy component typically produces a spectral peak at longer wavelengths. While Panofsky and Dutton (1984) report this peak around \( n=0.05 \) in neutral conditions in the atmosphere, Pond et al. (1971) observed peaks around \( n = 0.01 - 0.02 \) based on their numerous runs. The latter range of values also applies to the Anderson and Verma (1985) and Smith and Chandler (1987) studies reported above. There is thus no evidence that the peak in the \( u \) spectrum for the Fraser River data, in the range \( n = 0.02 - 0.05 \) (Fig. 13) is significantly shifted from this expected range for \( u \) turbulence.

3.1.2 The uv cospectrum.

The mean kinematic stress (\( -\langle u'v' \rangle \)) about the long-term streamline, calculated for a 2.33 hr period between 17:40 and 20:00 hours in the June 13, 1988 records is 28 cm\(^2\)/s\(^2\). This is equivalent to a shear stress (\( -p\langle u'v' \rangle \)) of 2.8 Pa (\( p \) is water density). At the approximately 10 m flow depths in the study reach near Mission such a shear stress would be typical of a steady flow with an energy
gradient of $3 \times 10^{-5}$. No data are available on energy gradient on the side-channel of the Fraser River, at this precise stage of runoff and phase of tidal backwater. Such an energy gradient however is of the right order of magnitude given what is known of the typical overall slope of the Fraser R. at Mission, at $5 \times 10^{-5}$.

The cospectrum of u' and v' fluctuations breaks down the total Reynolds stress reported above into component contributions over the range of frequencies of velocity oscillation. Cospectral estimates were computed from 21 time segments (with 50% overlaps) of uncorrupted flow data, each of 13.65 min ($2^{12}$ data points) length for the June 13, 1988 record. The level of coherence between the two series is limited (Fig. 15 a): coherence squared reaches a level of 0.5 only at lowest frequencies (although these low frequency estimates have more random variability than the rest). Mostly, coherence is around the typical turbulent value of 0.3 up to the instrumental roll-off above 0.5 Hz. Coherences under 1 generate even more sampling variability in the cospectrum than was present in the individual velocity spectra (Bendat and Piersol, 1986). To bring down the sampling variability, mean estimates from the 21 sets were further smoothed by averaging 20 adjacent frequency bins: this procedure degraded the frequency resolution to $(20/13.65 \text{ min})$ or 0.0244 Hz.

The results are presented in Fig. 15 b) in the conventional area preserving form. Also displayed is the U,V cospectrum extracted from the 57 minutes of records from Barnston Island described above, with mean stress somewhat lower than in the June 13, 1988 Mission conditions. For the Mission data, the integrated cospectral density between 0.0012 Hz and 2.5 Hz is $29 \text{ cm}^2/\text{s}^2$ ($20 \text{ cm}^2/\text{s}^2$ for the Barnston data). This is the same, within sampling variability, as the 2.33 hr long mean kinematic stress from the Mission record reported earlier. The contributions to stress between 0.0012 Hz ($T=13.65 \text{ min}$) and 0.00012 Hz ($T=2.33 \text{ hrs}$) thus appear minor overall. Because the lowest frequency estimate averages all the cospectral content between $f=0.00122$ ($T=13.65 \text{ min}$) and $f=0.0244 \text{ Hz}$ ($T=41 \text{ s}$)
Fig. 15:
(A, top): Coherence squared spectrum between the U and V signals, based on 2.2 hrs of records from June 13, 1988. Low frequency estimates are left unsmoothed. 20 estimate bloc means beyond 0.02 Hz.

(B, bottom): UV cospectra, superimposed, for main June 13, 1988 deployment near Mission and July 14, 1987 deployment at Barnston Island. See section 2.4 for flow conditions. Error bars represent standard deviations of cospectral densities.
it appears relatively high. The raw, unaveraged spectral estimates trend downward towards the longest period sampled (13.65 min).

Panofsky and Dutton (1984) report that the peak contribution to the uv cospectrum, per frequency decade, in the neutral atmospheric surface layer occurs near a non-dimensional frequency n=0.08. As seen above, in these surveys the non-dimensional and dimensional frequencies are numerically approximately the same, and so the location of the peak in Fig. 15 b) approximately conforms to this atmospheric standard. More noteworthy in Fig. 15 b) is the overall importance of the lower frequencies to total stress. In the Mission data, the relative contribution of motions between 0.0012 Hz (T=13 min) and 0.08 Hz (T=12.5 s) is 80% of the total stress (75% for the Barnston data). (Note that the abscissa is truncated at 0.01 Hz on Fig. 15 b), but the lowest spectral density represents oscillations down to 0.0012 Hz). Typical results for turbulent stress are again varied. Panofsky and Dutton (1984; their fig. 8.26) state that approximately 50% of the stress occurs below this value n = 0.08 in the neutral atmospheric surface layer. Soulsby (1980) reports a similar value from tidal boundary layer data. Large and Pond however (1981) present atmospheric uv cospectra in slightly unstable conditions over the ocean in which this contribution is 60% of the total.

To see if the multi-minute flow oscillations on the Fraser River produce a contribution to momentum exchange unusually large for turbulence, it is best to consider the cospectral contributions below n = 0.01, corresponding to oscillation periods greater than 1.7 min. The Mission cospectrum includes 27% of the total below this value and this proportion is 21% for the Barnston data. Thus close to a fourth of the total momentum exchange in the study data is caused by slow flow oscillations of period over 1.7 minutes. Both Panofsky and Dutton (1984; atmospheric data) and Soulsby (1980; tidal data) report a lower turbulent contribution to shear stress below n=0.01: between 5 and 10% of the total. Other near-neutral flows have been reported to contain low-frequency contributions of
the same scale as those found on the Fraser River, however. The Large and Pond (1981) records from the surface layer above the ocean include some 17% of the stress below $n = 0.01$, essentially the same as the Barnston Island result on the Fraser River. The $uv$ cospectra over field crops in near neutral conditions reported by Anderson and Verma (1985) include roughly a quarter of their area below $n = 0.01$. Because of the variability in turbulence statistics and the small number of study spectra, the above comparisons are preliminary and tentative.

In summary, the available results do not point to a level of contribution to stress by multi-minute oscillations that is clearly unusually large for boundary layer turbulence. The absence of a spectral "gap" in $u$, $v$ or $uv$ spectra (Figs. 13, 14, 15 b), around periods of the order of a minute ($f=0.017$ Hz), further suggests that turbulent processes may occupy the whole range of frequency content in the Fraser data. The cospectral peak at $f=0.07-0.1$ Hz in Fig. 15 b) nonetheless indicates that the most important contributions to stress correspond to 10 to 15 s scale turbulent events. Large turbulent motions in this class will be analysed further in what follows.

3.2 Intermittent contributions to momentum exchange.

Complex turbulent "bursting" structures are best perceived through flow visualization (e.g. Kline et al, 1968) and the study of simultaneous flow records at different heights above the wall (e.g. Nakagawa and Nezu, 1981). Nonetheless various attempts have also been made to detect the passage of these structures from flow series at one point, such as were gathered in this study (cf section 1.1). Unfortunately, whether they are identified through pulsations in high-frequency turbulence intensity at one point (e.g. Rao et al, 1971) or high magnitudes of $(u'v')$ (e.g. Lu and Willmarth, 1973), considerable latitude remains in defining and counting such $(u'v')$
"events", as well as in relating them to the classic bursting process. In the next two sections the Fraser River (u'v') records will be analysed in the light of two criteria conventionally used to identify turbulent bursting in geophysical (u'v') records: high intermittence of stress contributions and mean "event" recurrence conforming to the "outer scaling" identified in the laboratory. The aim of this analysis is to compare properties (degree of intermittence, recurrence periodicity) of burst-like stress "events" in the Fraser River to those reported in laboratory as well as tidal and benthic boundary layers.

3.2.1 Intermittence of (u'v') time series at sensor level.

Bursts are known to account for most of the turbulence production and momentum exchange in a boundary layer and the latter property can produce a signature identifiable on (u'v') records. Between adjacent zero crossings of the (u'v') time series, individual "events" are classified as "ejections" (u'<0, v'>0), "inrushes" (u'>0, v'<0), and "negative stress" producing inward (u'<0, v'<0) and outward (u'>0, v'>0) "interactions". The first two event types dominate the records and lead to positive mean momentum exchange. Larger burst structures are typically associated with a pair of strong ejection/inrushes in the u'v' record. Typically, the recurrence of such large events leads to an intermittent (u'v') record: although occupying only a small fraction of time the intense events account for much of the mean stress.

Fig. 16 presents 14 minutes of the (u'v') time series on June 13, 1988 near Mission along with the low-frequency component of horizontal velocity fluctuations (low-passed with half-power at T=30 s). The plotted series start at 16:57 hr, as in Fig. 11. One second means of (u'v') have been plotted in Fig. 16 to allow the display of a longer time segment and larger events are labelled as ejections or inrushes. The 1 s mean produces very limited smoothing as fluctuations faster than 1 Hz contribute little to the total
Fig. 16: A 14 min time series of $(U'V')$, indicating instantaneous momentum exchange through the sensor level, along with simultaneous low-frequency fluctuations in $U$. June 13, 1988 deployment near Mission. Large events marked E and I are respectively "ejections" ($U'<0$, $V'>0$) and "inrushes" ($U'>0$, $V'<0$).
stress (cf. Fig. 15 b); all subsequent \( (u'v') \) statistics will nonetheless be based on the recorded velocity fluctuations at 5 Hz. Immediately apparent are large negative spikes in \( (u'v') \) of 5-10 s duration; many of these events reach or exceed a level equal to 5 times \((-150 \text{ cm}^2/\text{s}^2)\) and a few even 10 times \((-300 \text{ cm}^2/\text{s}^2)\) the mean \(<u'v'>\). The aggregate contribution of these brief events is considerable; thus the momentum exchange is intermittent.

Gordon and Witting (1977) found that strong events occupying only 25% of the record time accounted for essentially all the momentum exchange 2 m from the bed of a tidal channel. Although conventional by now, such statistics are somewhat misleading: events other than those tallied in this 25% may not be of minor significance to momentum exchange, as implied; rather their positive and negative contributions might simply cancel each other. Despite this qualification, such statistics nonetheless offer a ready measure of intermittency that can be compared to previous findings.

On the Fraser River near Mission the intermittency can be illustrated by a similar comparison of the fraction of time versus fraction of total momentum exchange due to \( (u'v') \) values below a certain threshold (Fig. 17, based on 2.2 hr of data on June 13). As in Gordon and Witting's (1977) data, \( (u'v') \) values exceeded only 25% of the time (here below \(-50 \text{ cm}^2/\text{s}^2)\) "account" for all the mean stress. Analysis of more extreme \( (u'v') \) levels indicates that, while values below \(-100 \text{ cm}^2/\text{s}^2\) account for close to 80% of the exchange, they only occupy 12% of the time, while more than 30% of momentum exchange can be thought of as occurring during 3% of the time (values below \(-200\)).

Intermittency, in the sense used here, is related to the high degree of kurtosis in the \( (u'v') \) probability density; if extreme amplitude events are relatively frequent in a skewed distribution they tend to dominate overall averages (here of course average \( u'v' \) is the stress). Table 2 presents summary statistics for \( u' \), \( v' \) and \( (u'v') \) distributions based on the 2.2 hr of data for June 13, 1988. By subtracting the value 3, kurtosis here was defined as
First of data from June 13, 1988 deployment near Mission.

Settles exceeds various threshold values, based on 2.2
stress associated with periods when the
Fig. 17: Percent of time and percent of mean kinematic

\( \left( \text{cm}^2/s \right)^2 \) (\( \gamma \))

- Time
- Stress

Percent of time or stress

7.00 - 600 600 - 400 400 - 300 300 - 100 0 100 200 300 400

0.01

0.1

1
TABLE 2
MOMENT STATISTICS FOR $u'$, $v'$ AND ($u'v'$) DISTRIBUTIONS

period 17:42-19:56 hr PST, June 13, 1988
velocities in cm/s

<table>
<thead>
<tr>
<th></th>
<th>$u'$</th>
<th>$v'$</th>
<th>$u'v'$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>40266</td>
<td>40266</td>
<td>40266</td>
</tr>
<tr>
<td>MEAN</td>
<td>0.0</td>
<td>0.0</td>
<td>-27.9</td>
</tr>
<tr>
<td>STAND. DEV.</td>
<td>12.5</td>
<td>5.5</td>
<td>73.6</td>
</tr>
<tr>
<td>SKEWNESS(G1)</td>
<td>0.2</td>
<td>-0.1</td>
<td>-1.9</td>
</tr>
<tr>
<td>KURTOSIS(G2)</td>
<td>-0.4</td>
<td>0.2</td>
<td>7.4</td>
</tr>
</tbody>
</table>
being zero for a normal distribution. While both \( u' \) and \( v' \) are near normal, \( (u'v') \) is negatively skewed and has quite heavy tails. The product of two near normal variates that are correlated, such as \( u' \) and \( v' \), is generally expected to have "heavy tails" (i.e. positive kurtosis; Kennedy and Corrsin, 1961; Antonia and Atkinson, 1973); however the precise degree of kurtosis can vary, and it is one measure of degree of intermittence. What is of interest here is thus how the degree of kurtosis (and hence intermittence) in the study conditions compares to that reported in other flows.

The fluvial results in Table 2 are typical of those obtained in laboratory and large-scale flows (Antonia and Atkinson, 1973; Anwar, 1981). Notably, the kurtosis of \( (u'v') \) near the bed of the Fraser was of the same order (7.4 at Mission, 6.9 for the Barnston data) as values found by others at comparable distances from the bed in large-scale flows (McLean and Smith, 1979; Heathershaw, 1979). To graphically illustrate the degree of kurtosis in play here, Fig. 18 compares a histogram of \( (u'v') \) values recorded on June 13 and a normal distribution of same mean and standard deviation. The frequencies of occurrence of values of \( (u'v') \) below \(-200 \text{ cm}^2/\text{s}^2\) are orders of magnitude higher than "normal".

### 3.2.2 Mean burst recurrence period

Momentum exchange is thus dominated by repeated intense but brief events and this is a known characteristic of bursting structures investigated in the laboratory. The usual way of further establishing a link between such one-point \( (u'v') \) "events" and near-wall bursting is to compare the mean recurrence period for these events, \( T_b \), with the laboratory outer flow scaling for burst recurrence. Do the Fraser River observations confirm the conventional outer flow scaling of burst recurrence?

As in much preceding work (cf. section 1.1), it is difficult to define completely objectively a mean recurrence period for these intense burst-like events in the Fraser data. Fig. 19
Fig. 18: Histogram of observed \((U'V')\) values compared with that of a normal distribution with same mean and standard deviations. Ordinates are expressed as percent time. Based on 2.2 hrs of data from June 13, 1988 deployment near Mission.
Fig. 19: Observed mean recurrence periods of intense "ejections" during which the -(U'V') signal exceeds various threshold values. Based on 2.2 hrs of data, June 13, 1988.
presents the statistic mean time between strong ejections against the threshold \((u'v')\) value used to separate these events from background, based again on the 2.2 hr of main study data (June 13, 1988). The recurrence periods are in the minutes range and increase continuously as threshold is set further from the mean. Although this increase is most rapid at more extreme values of threshold, there is no apparent "natural" mean recurrence period, \(T_D\), in the sense of being substantially independent of threshold level. Fig. 20 superimposes burst recurrence curves from the June 13, 1988 records with those of two other study deployments (cf. section 2.4). To allow comparison, the stress threshold has been scaled by mean stress applicable to each deployment. The curves are rather similar and in rough agreement for higher stress levels.

In a detailed investigation of the \((u'v')\) event-counting procedure, Willmarth and Lu (1974) had already pointed out the continuous variation of burst period with \(u'v'\) threshold level, even in simpler laboratory flows. Fig. 21 presents the dependence of recurrence period on threshold setting in their wind tunnel experiments. It can be seen that the absence of a natural plateau in the curve on which to base a threshold setting is not a feature unique to our fluvial data; it also occurs for classic bursting in lower Reynolds number flat wall flows.

The observed burst recurrence period on the Fraser River will thus depend, as in all such studies, on the judicious selection of a threshold value to separate bursts from background stress activity. Willmarth and Lu (1974) argued for setting the event-defining threshold at about 10 times the mean kinematic stress, as contributions of events other than ejections gradually disappeared above this value in the outer parts of the flow. Furthermore, they showed this 10X threshold to be consistent and useful even into the middle and outer portions of the boundary layer (which corresponds to the study conditions) and to produce recurrence periods matching those of Rao et al (1971). To date, theirs would appear to be the best documented threshold setting for the uv quadrant method applied
Fig. 20: Superimposed curves of ejection recurrence periods for \(-(U'V')\) events exceeding various threshold values. Details on flow conditions during three deployments can be found in section 2.4. Stress thresholds are normalised by mean stress during each deployment.
Fig. 21: Mean recurrence periods of intense "ejections" as a function of $u'v'$ threshold setting and distance from wall (solid and open symbols) in wind tunnel experiments. From Willmarth and Lu, 1974 (their Fig. 18). Ordinate is recurrence period $T_B$ non-dimensionalised by outer variables. Abscissa is threshold stress normalised by the product of rms of $u$ and $v$. Hole size of 4.5 corresponds to 10 times mean stress.
to outer flow observations, and will thus be used here. Applying Willmarth and Lu's criterion to the June 13, 1988 Mission data (Fig. 19) it is found that ejections with \((u'v')\) below approximately \(-290 \text{ cm}^2/\text{s}^2\) (ten times the mean) recur every 8 minutes on average (based on 2.2 hr of data). Fig. 20 suggests that in general on the Fraser River this period varies between 5 and 10 minutes. How do these values compare with predictions based on conventional outer flow scaling?

The boundary layer thickness (or momentum displacement thickness in some studies) is a key parameter in this scaling. No study has been conducted on whether the burst scaling in an open channel boundary layer is affected by the presence of a free surface, which in effect imposes a limit, irrespective of fetch, on the depth of the layer. Until this matter is clarified, and to avoid confusion, the usual assumption for river flows is best followed. Thus the boundary layer thickness will be taken to correspond to the full flow depth. In the June 13 study conditions, with 10 m flow depth \(H\) and 1.4 m/s surface ("free stream") velocity \(U_s\), the conventional Rao et al (1971) scaling:

\[
\frac{T_b}{H} = \frac{U_s}{H} = 3 \text{ to } 7
\]

predicts a mean burst recurrence period \(T_b\) between 20 and 50 s. This is an order of magnitude below the value (8 min) computed from the June 13 data using the Willmarth and Lu (1974) threshold setting. As discussed previously, the basis and validity of these authors' threshold was established in laboratory comparisons of flow signals over a range of distances from the wall (and thus cannot be further verified here). It was claimed by the authors however to produce \(T_b\) values consistent with the outer flow scaling in such flows, and as such is one of the few objective and documented threshold criteria available for \((u'v')\) records away from the wall layer. In all conditions reported in Fig. 20, outer flow scaling would have predicted recurrence periods well under 1 minute, much below
observed periods.

3.3 Modulation of turbulent bursting over bedwaves: a speculative interpretation of the above results.

The previous analysis revealed the existence of intermittent and intense \((u'v')\) events in the study data. These events however appear to be less frequent than expected according to conventional views of bursting in this environment. In this section, the possible relation between these events and classic laboratory-scale bursting will be discussed. As explained in chapter 1, the spatially limited (one point) field data cannot conclusively settle this issue. Since the usefulness of the bursting "model" to alluvial flows is of basic interest to students of river mechanics, speculation will be attempted, based on the study data, on possible links between the study events and conventional bursting. Possible interpretations of the stress events in Fig. 16 that largely deny the role of classic bursting will first be considered.

It could be argued that the presence of multi-scale boundary deformation (small bedforms over larger) in typical river flows may effectively drown out any distinguishable bursting signal within multiple scales of flow perturbations, eddy shedding in the lee of bedforms, etc. If such were the case, it might not even be appropriate to talk of "identifiable burst-like events" in the fluvial context. The study observations do not particularly support this extreme view, however. Stress "events" in the study data do not appear to be less "distinct", in a technical sense, than those identified over simpler boundaries in the laboratory. Very intense \((u'v')\) events are quite identifiable in the record from the Fraser River (Fig. 16). Moreover, the multiplicity of scales of \((u'v')\) events in flat wall laboratory flows themselves must not be underestimated. If two populations of \((u'v')\) values (background
values and much less numerous intense values) were clearly more
distinct (better separated) in the laboratory than in the river
flows, a much higher kurtosis in the \((u'v')\) distribution might be
expected in the former than in the latter. However kurtosis values
in laboratory flows (e.g. Antonia and Atkinson, 1973) were seen to
be roughly comparable to those in the study data (table 2). A very
gradual change in burst counts (and mean period) with \((u'v')\)
threshold, similar to that documented on the Fraser (Fig. 20), was
also reported in a lower Reynolds number, laboratory flow (Fig. 21).
In summary, significant \((u'v')\) "events" in the study records appear
neither clearly more nor less "conspicuous" or identifiable than
they are in laboratory flows. The parameters of their intermittence
are quite similar to those reported from other flows, even if they
appear to recur less frequently than expected.

Could simple eddy shedding from the lee faces of dunes on
the bed, a possible alternate generating mechanism for large scale
eddies in river flows (e.g. Rood and Hickin, 1989), be responsible
for the signals in Fig. 16? Based on a strict definition of eddy
shedding, the proposal seems unlikely. On the one hand, "shed"
eddies typically travel along the separation bubbles in the lee of
dunes, towards flow reattachment points; they are thus unlikely to
be ejected upward away from the dune wake layer into the outer parts
of the flow (and even appear as surface "boils", as argued by Rood
and Hickin, 1989). It is possible rather that true burst structures,
themselves propagating away from the bed, may trigger (via pressure
effects) eddy shedding as they travel from their inception on the
dune stoss side over the following dune separation zone.

More tellingly, individual burst-like events in Fig. 16 have
durations of 5 to 10 seconds, roughly matching the peak in stress
spectrum (Fig. 15 b). If due to turbulent effects, such periods are
well within the energetic turbulent range for which "Taylor's
scaling hypothesis" may be useful. If, as hypothesised, the
disturbances are indeed "shed" into the mean flow, given their
periods they would represent structures of considerable streamwise
extent \((5-10 \text{ s} \times 1 \text{ m/s} = 5-10 \text{ m})\) convecting past the sensor at near mean flow velocity. However, eddies shed from obstacles by definition scale with the dimensions of the obstacles, and the largest dunes present in the Mission reach have heights of order 1 m only; such dune-shed eddies would likely be much smaller than the burst-like structures of length 5-10 m identified in Fig. 16.

Could bursting be responsible for the observed signals? It appears to be accepted in the fluid dynamics literature that burst structures are identifiable (despite difficulties) and that their recurrence conforms to the outer scaling at least over 2 orders of magnitude of flow Reynolds numbers (Rao et al., 1971). Grass (1971) also documented the existence of bursting over flat sedimentary boundary layers in the laboratory, even when roughness disrupts the viscous sublayer. For lack of clear evidence to the contrary, it is reasonable to assume that the bursting phenomenon may not be totally repressed in even higher Reynolds number river flows (the details of the process may be modified, of course). If these assumptions hold, then one can tentatively associate bursting with the large events in Fig. 16.

It would remain to be seen, then, why burst passage at the sensors might be less frequent than in laboratory conditions. It can be argued that burst recurrence should be significantly affected by the presence of bedforms on the flow boundary. Busting activity is sensitive to downstream pressure gradients (Kline et al., 1967) and these are spatially varied near river dunes (e.g. Raudkivi, 1964). On theoretical grounds, a degree of modulation of turbulent stress activity might be expected as bedforms advance relative to the fixed sensor. This modulation would reflect the variable amount of bursting activity that occurs on the area of bedform, whether stoss or lee, that happens to lie just upstream and generates most of the large motions passing the sensor at any moment.

These theoretical ideas find some support in published observations. Buckles et al. (1984) document the superposition of eddy motions convected from the intense shear on the stoss side of
sinusoidal bedwaves and the wavy streamline field away from the bed. They show in particular how any vertical profile of turbulence intensity over such a bedfield is marked by successive maxima, corresponding to the free-shear layers detached from successive bedforms upstream, each rising obliquely into the flow. Given advancing bedwaves and a fixed sensor, the existence of these layers of variable turbulent intensity would modulate in time the turbulence at the sensor, and presumably large burst passages. Other studies of the turbulent flow in the vicinity of beds formed into pure sine waves have documented cyclic spatial variations in turbulence intensities and Reynolds stresses in the flow over these waves (e.g. McLean and Smith, 1979; Hsu and Kennedy, 1971). Iseya (1984) observed peaks in vertical turbulence intensity (variance of $v''$) over the stoss sides of laboratory sand dunes when the flow sensor was just over the level of wave crests. Itakura and Kishi (1980) observed that bursting structures over laboratory sand waves occurred preferentially near the reattachment point on the stoss side and then convected outward, eventually passing over the back of the next waves.

In this way, a fixed sensor over advancing bedwaves might well be affected by cyclic modulations of turbulent burst activity. This possibility implies that mean burst periodicity at a fixed sensor position in the fluvial context could depend on relative location of the sensors within the bedform geometry, bedform advance rates, in addition to those outer flow parameters identified in flat wall boundary layers. Such an outcome may explain the apparently anomalous recurrence periods observed on the Fraser River. The location and movement of small bedwaves relative to the sensors could not be resolved with sufficient accuracy in the study conditions to address these issues.
3.4 Isolating purely turbulent contributions to momentum exchange

There is another particularity of the time series of burst-like motions above the Fraser River bed that is worth reporting. The strong multi-minute flow cycles on which are superimposed the faster turbulent motions (cf. Fig. 11) impose a characteristic modulation of ejection/inrush motion which has not, to the author's knowledge, been reported elsewhere. During the multi-minute phases when the mean streamline at the sensors is downward, turbulent (higher frequency) \( v' \) fluctuations convected past the sensor are superimposed on a negative minute-scale-average \( v' \). The resultant measured \( v' \) fluctuations are as a consequence biased negatively: upward motions are uncommon and downward ones are proportionally exaggerated. The opposite holds during minute scale periods when the average streamline points upward.

The effect of this modulation can be well seen in Fig. 16. The low-passed \( u \) signal is a very good indicator of average streamline orientation in a given period; typically the flow is accelerated when oriented towards the bed (negative \( v' \)) and decelerated when it tends to be oriented upwards (positive \( v' \)) (cf. Figs 8, 9). While normally in a boundary layer ejections and inrushes tend to occur in rough sequence, strong inrushes in Fig. 16 are systematically grouped during periods of high \( u' \) (negative \( v' \)), and strong ejections during ones of low \( u' \) (positive \( v' \)).

This modulating effect of the multi-minute flow cycles on the distribution of ejection/inrush events can be partly filtered out, in effect concentrating attention on the "burst-scale" turbulent velocity fluctuations and their contribution to stress. To this end, the \( u' \) and \( v' \) records were digitally high-passed (hp) filtered, with a filter half-power point set at a period of 30 s to exclude most of the multi-minute flow oscillations.
The chosen filter of course cuts off much of the lower frequency turbulence (below \( n = 0.033 \)) along with any longer nonturbulent oscillations. Nonetheless, ejections usually documented at 1-2 m distances from the bed in tidal flows have time-scales in the 5-15 s range (Gordon and Witting, 1977; Heathershaw, 1979) and would thus "pass through" the filter. A smooth Gaussian filter was employed to extract the low frequencies. The instantaneous high-frequency contribution to momentum exchange was then computed as the product of high-passed \( u' \) and \( v' \) signals (\( \text{hp-}u'\times\text{hp-}v' \)).

Fig. 22 presents a 14 minute time series on June 13, 1988 of this high frequency turbulent stress (1 second means) against \( \text{lp-u'} \), the low-passed horizontal velocity fluctuations at the sensor prevailing at the same time. The mean kinematic stress due to these high frequencies is 7.5 cm\(^2\)/s\(^2\) approximately (down from 29 for the unfiltered record). Intermittence of momentum exchange is still obvious, as it is concentrated in the burst-scale high-passed components. While clearly much of the stress bearing frequencies have been filtered out, the interest here is not in the total stress but only in the arrangement of the 5-15 s period intermittent "events", already visible in Fig. 16, once they have been extracted from the strong low-frequency flow oscillations. The effective removal of the multi-minute \( u'v' \) fluctuations from the velocity records has sharply reduced the segregation of ejections and inrushes discussed previously with reference to Fig. 16; these are more evenly mixed in Fig. 22. Such an effect has not, to the writer's knowledge, been reported previously.

3.5 Summary of findings.

In summary it can be stated that momentum exchange at 1 m off the bed in the study conditions is dominated by brief but intense events, not unlike those seen in laboratory and other
Fig. 22: A 14 min time series of the high-frequency contributions to momentum exchange at sensor level, along with simultaneous low-frequency horizontal velocity oscillations. June 13, 1988 deployment. Dashed line at 10 times mean high-frequency stress component $<(h_p-u'\cdot h_p-v')>$. 
large-scale channel flows. In what way these events are related to bursting is difficult to establish simply from event counts at one sensor level. The usual considerable subjectivity in the burst count approach (especially in defining an appropriate event threshold, cf. section 1.1) affects the usefulness of the method as a bursting diagnostic in the field. Assuming that the burst-like events identified at 1 m on the Fraser R. are related to turbulent bursting, and that Willmarth and Lu's (1974) criterion is indeed applicable, the evidence presented above points to somewhat longer burst return periods than conventionally expected. For sediment transport modeling, it may be more practical to recognize a continuous distribution of intense stress events, their recurrence period increasing with their relative magnitude (cf. Fig. 20).

The lack of strict conformity to the recurrence scaling of burst events established in the laboratory is not totally surprising. The study flows are of much higher Reynolds number than laboratory models, and have a slightly stable density stratification due to sediment suspension. The presence of active bedforms of various scales on the flow boundary may also invalidate the scaling conditions established over flat walls in the laboratory. The instantaneous location of the sensor within the spatially modulated field of shear stresses and pressure gradients near river dunes is likely, in addition to the overall outer flow parameters U and H, to affect the intensity and timing of recorded \( (u'v') \) events. A fixed flow sensor overlying an advancing dune field might for example see periods of greater and lesser turbulent activity, depending on whether at any time it lies close to, or well away from, the centre of the trajectory of the large structures convected from active bursting zones. Such speculation would best be tested in the laboratory where bedform motion can be more easily documented.
The simultaneous time-series of turbidity values provided by the Optical Backscatter Sensor (OBS) alongside the velocity meter will be analysed in this chapter to clarify the impact that flow fluctuations of different frequencies have on sediment suspension 1 m from the bed of the Fraser River. The central issue in this chapter is to what extent strong "ejection-like" motions passing through this level correlate with peaks in suspended sediment concentration, and what is their resultant importance to total vertical sediment flux. As in previous chapters, the main conclusions drawn on the basis of the data from June 13, 1988 will be backed up by records from other deployments.

The time series of OBS output plotted previously (Figs 8, 9, 11) illustrated the existence of fluctuations in turbidity level with time scales extending from seconds to tens of minutes. Furthermore these fluctuations qualitatively displayed obvious correlation with velocity cycles at corresponding frequencies. However, before analysing these relations in greater detail, the correspondence between OBS returns (in mV) and actual suspended sediment concentrations at sensor level must be clarified.

4.1 OBS output as a measure of suspended sediment concentration.

As explained in section 2.2.2, the OBS output must be calibrated to actual samples of suspended sediments collected at sensor level. Although theory predicts that OBS output increases linearly with concentration of any given size fraction in suspension, the sensitivities are not the same for every fraction while the proportions of clays, silts and sands in near-bed
suspensions are expected to vary in a complex way through turbulent events. Thus, the resultant field calibration regression between total suspended concentration and OBS returns over full scale need not even be linear, unless the proportions of the different fractions are essentially fixed in the study environment.

In practice it is not physically feasible to sample the suspension at the time resolution which the optical sensor can itself achieve. During the June 13, 1988 deployment near Mission, reasonably short duration (7 s) samples of the fluid were collected just behind the OBS sensor through a pipe intake of 1 cm internal diameter, with an intake velocity adjusted to match the mean horizontal flow velocity at sensor level (cf. Fig. 1, bottom). This procedure produced 27, half-litre samples which were filtered in the laboratory and analysed for the concentrations of suspensates of different size fractions. By carefully recording the sampling period on deck and accounting for the sample travel time from pipe intake to the surface, the actual sampling period at the intake was derived with an accuracy of one second. This procedure in turn allowed the mean OBS return during the intake period, as well as the corresponding mean horizontal and vertical velocity components, to be extracted from the records.

Fig. 23 presents the particle size analysis for 27 samples gathered on June 13, between 14:00 and 20:19 hrs, along with the mean OBS return corresponding to each sample. Although samples are numbered in time sequence the cycles evident in the series are spurious, and reflect aliasing of the intense high frequency concentration fluctuations in physical samples spaced tens of minutes apart. Despite being usually thought of as quite homogeneously mixed and steady in the water column, the concentration of silts and clays (D<0.063 mm), conventionally taken as the washload, does vary somewhat in harmony with coarser bed
Fig. 23: Grain size analysis and concurrent OBS response for 27, 7 second duration suspended sediment samples drawn behind the OBS unit. June 13, 1988 deployment.
TABLE 3
STATISTICAL DATA ON OBS CALIBRATION SUSPENDED SEDIMENT SAMPLES. N=30
June 13, 1988, near Mission

<table>
<thead>
<tr>
<th>Fraction retained on sieve of given size (within stack), (μm)</th>
<th>Mean</th>
<th>Standard dev.</th>
<th>Coef. of Var.</th>
</tr>
</thead>
<tbody>
<tr>
<td>355</td>
<td>4</td>
<td>2.6</td>
<td>0.65</td>
</tr>
<tr>
<td>250</td>
<td>86</td>
<td>44</td>
<td>0.51</td>
</tr>
<tr>
<td>180</td>
<td>112</td>
<td>38</td>
<td>0.34</td>
</tr>
<tr>
<td>90</td>
<td>108</td>
<td>25</td>
<td>0.23</td>
</tr>
<tr>
<td>63</td>
<td>27</td>
<td>5</td>
<td>0.19</td>
</tr>
<tr>
<td>passing 63 μm</td>
<td>103</td>
<td>7</td>
<td>0.07</td>
</tr>
</tbody>
</table>

CONCENTRATION DATA (mg/1)

PEARSON CORRELATION MATRIX

Cd is the concentration retained on sieve size d (μm)

<table>
<thead>
<tr>
<th></th>
<th>C355</th>
<th>C250</th>
<th>C180</th>
<th>C90</th>
<th>C63</th>
</tr>
</thead>
<tbody>
<tr>
<td>C355</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C250</td>
<td>0.38</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>C180</td>
<td>0.15</td>
<td>0.41</td>
<td>1.00</td>
<td></td>
<td></td>
</tr>
<tr>
<td>C90</td>
<td>0.21</td>
<td>0.25</td>
<td>0.75</td>
<td>1.00</td>
<td></td>
</tr>
<tr>
<td>C63</td>
<td>0.36</td>
<td>0.28</td>
<td>0.21</td>
<td>0.40</td>
<td>1.00</td>
</tr>
</tbody>
</table>
material fluctuations (consider samples 5, 7 and 21 in particular). Nonetheless the relative stability in silt and clay concentration is notable when compared to that of the coarser sand concentrations. Summary statistics on the distributions of the different fractions in Table 3 clearly show increasing coefficients of variation (and in most cases standard deviations) of concentration from the silt-clay to the medium sand fractions. Three samples included in Table 3 were excluded from Fig. 23 because of corrupted OBS data.

Furthermore the different sand fractions vary together coherently: the correlation coefficients among the major sand fractions present (0.09<D<0.355 mm) range from 0.25 to 0.7. These relations illustrate the effect that fall velocities, as they increase with sediment size, have on ease of suspension. On the one hand, hydraulic conditions that can suspend heavier particles will also increase the concentrations of finer materials, within the limits of the latter's availability on the bed. Thus the positive correlations between practically all the fractional weights. The coarser the fraction however, the less stable and more dependent is its suspension on short lived and randomly occurring hydraulic forces, and so the more variable its presence in samples at sensor height, as seen in table 3.

The tendency for the different fractions in suspension to vary together with some degree of harmony leads to resultant backscatter intensities which track total concentration reasonably well, as is apparent in the correspondence between the OBS return and total concentration series in Fig. 23. Indeed the correlation coefficient between OBS return and total sample concentration is 0.90 for the 27 samples. The scatter plot of this relation in Fig. 24 indicates that a linear regression model does produce a good fit within the range of the data, with a standard error of estimate of the total concentration of 42 mg/l. Albeit imperfect, calibrations of sensor output for rapid concentration fluctuations as in Fig. 24 represent the present state of the art, given the response of optical or dynamic sediment concentration meters in environments
Fig. 24: Scatter plot and least square regression line establishing a calibration of OBS output in terms of total sample suspended sediment concentration. June 13, 1988 deployment.
with variable mixtures of particle sizes (cf section 2.2.2).

As in other studies of suspension time series (Soulsby et al, 1984, 1985; West and Oduyemi, 1989), the analysis of concentration spectra and sediment fluxes will assume nominally accurate calibrations. Where appropriate, the possible effects of calibration errors on study conclusions will be discussed. The regression model of Fig. 24 implies that OBS output needs to vary by more than approximately 140 mV, based on 7 seconds samples, for associated concentrations to be significantly different (at 95% level). Thus, typical peak to peak turbulent fluctuations in the OBS series, with amplitudes of the order of 150-400 mV (Fig. 11), represent real fluctuations in concentration.

A key assumption in this study is that observed fluctuations in OBS output essentially reflect variations in suspension of the sandy "bed materials" near the frame, rather than random "wash load" fluctuations unrelated to local entrainment. This is a concern since the OBS sensor is disproportionately sensitive to fluctuations in silt/clay concentrations. The precise calibre of sediment defined as wash/bed material cutoff is however somewhat arbitrary, as there is in reality a fairly broad transition in behaviour with varying sediment size. Furthermore the range of sediment sizes transitional in behaviour between wash and bed material depends on the sedimentary and hydraulic environment.

McLean and Church (1986) argue that 0.125 mm, rather than the conventional 0.063 mm, constitutes a proper cutoff between bed material and wash loads on the Fraser River near Mission. They note that very fine sands, of calibre less than 0.125 mm, represent only some 2% of bed materials in this reach and that their suspension shows clear "exhaustion" effects (hysteresis) during a typical freshet. However, bed materials may have been marginally finer in the side channel of the Fraser River monitored and no precise wash load cutoff can be determined on the basis of the data of June 13. The sample data nonetheless indicate that even very fine sand contents (0.063 mm < D < 0.090 mm) appear to fluctuate coherently
with coarser fractions, suggesting that enough may be accumulated on
or near the bed to make them responsive to local micro-scale
hydraulic events.

Whatever cutoff is used to define bed materials, the sample
data establish that observed OBS fluctuations essentially reflect
variations in concentrations of fine and medium sands, presumably
from entrainment at the bed locally. While the correlation
coefficient between OBS output and the concentrations finer than
0.063 mm is only 0.26, it is 0.85 with the concentration of
suspended sands coarser than 0.090 mm. Fig. 25 presents the scatter
plot and regression of this latter relation: the standard error of
prediction of concentration of "bed materials" coarser than 0.090 mm
is 49 mg/l. The marked outlying point corresponds to sample 7 (Fig.
23) which was exceptionally poor in silts and clays and thus
produced unusually low backscatter reflection for its sand content.
Note that the precise cutoff figure used here, 0.090 mm, should not
be taken as the wash/bed material boundary. In part it is simply an
artefact of the choice of sieve sizes used in the analysis.

The sampling data also indicate that higher sand
concentrations in the samples tend to correlate with positive
(upward) vertical velocities at the sensor (correlation coefficient
of 0.33 between mean vertical velocity and concentration of sands
coarser than 0.09 mm) as well as with horizontal velocities that are
below average (correlation of -0.47). Since the latter statistics
are based on only 27 sample values within one run (or flow) they are
susceptible to significant sampling error. It is interesting to note
that over the ocean Phelps and Pond (1971) similarly found that
turbulent fluctuations in air humidity content had correlations of
the order 0.3 with v' and -0.5 with u'.

Although the above results are clearly compatible with the
hypothesis that upwelling events are responsible for suspending
sands from the bed, such isolated mean velocity values do not allow
the necessary distinctions to be made between the suspension effects
of turbulent motions at different frequencies, and in particular
Fig. 25: same as Fig. 24, for a calibration of OBS output in terms of the concentration of the sand fractions coarser than 0.09 mm.

\[ C' = 1.22 \text{ OBS} - 1973 \]
\[ R^2 = 0.72 \]
\[ \text{S.E. of estimate} = 49 \text{ mg/l} \]
those of burst-scale events. The latter analysis is best conducted on the basis of the more complete time series of velocities and OBS output and will be the subject of the next section.

While the calibration errors in the regression models are clearly related to fluctuating proportions of coarser sands in the suspended samples, the latter variable is not significantly correlated with mean $u$ or mean $v$ conditions at the time of sampling. The calibration result will later be used to compute vertical sediment fluxes ($C'v'$) based on the combined OBS and $v$ records.

4.2 Vertical velocity and sediment concentration fluctuations at the 1 m level.

Since the strongest gradients of mean sediment concentration near the bed are vertical, the vertical velocity fluctuations responsible for mixing across this gradient, and maintaining sediment transport in the face of sediment fall velocities, have long been of main interest to the students of sediment transport mechanics. For such theoretical reasons, the study will focus on the relations between the OBS and $v'$ (rather than $u'$) signals. Although the simple mechanism of concentrated sands being thrown up by energetic bursting events is the focus of this enquiry, such events nonetheless have to be extracted from a complex background, involving among other things strong multi-minute fluctuations in both OBS and $v$ signals (cf. Figs. 8, 9). There is no clear evidence, based on the spectral analysis reported in section 3.1, that any other process than boundary layer turbulence need be involved in these multi-minute flow oscillations. Nonetheless, the existence of significant multi-minute cycles in suspension activity has not been extensively documented previously in large rivers. It may qualify in important ways the widespread view (e.g. Matthes, 1947; Jackson, 1976) that burst-scale events (here of duration 5-15 s, see section 3.2) dominate sediment suspension. For these reasons,
the statistical association between the OBS and v signals will be analysed first with respect to their different frequency bands. In a later section (4.4.2), the relative importance of the multi-minute motions to the aggregate vertical suspension flux will be quantified. As in the previous chapter, this frequency domain analysis of the signals will be complemented by an analysis of suspension in terms of the timing and importance of discrete burst-like events, the main focus of this study.

4.2.1 Statistical analysis of the relation between the v and OBS signals.

In chapter 3 (Fig. 12), a power spectrum of OBS response (dashed line) was superimposed on those of u and v fluctuations based on 2.2 hours of data from June 13, 1988 near Mission. The bulk of the turbidity oscillations occurred at frequencies below 0.1 Hz (T>10 s). In the atmosphere, spectra of scalar contaminants (e.g. temperature, humidity) are typically similar to that of the u component (e.g. Anderson and Verma, 1985); in the Mission data, the OBS spectrum appeared to be somewhat intermediate in shape between the u and v spectra, with a peak around n = 0.06-0.08. Clearly, numerous replicate OBS spectra must be acquired in further studies if one wanted to verify any general similarity between the OBS spectrum and that of either u or v flow components for river flows.

To the extent that vertical flow motions drive sediment concentrations at sensor level, a degree of correlation between the OBS and v cycles is to be expected. However, are the multi-minute flow cycles as important as the burst-scale motions in "controlling" suspension? This section will start addressing this question, by investigating the statistical strength of the relation between the OBS and v fluctuations within broad frequency bands. To more accurately assess the relations between turbidity and multi-minute vertical motions, the analysis is based on the longest uncorrupted record available, from June 13, 1988.
Fig. 26 presents time series of 1 minute means of OBS output along with u and v velocities, starting at 17:42 hrs on June 13, 1988. Estimates of suspended sand concentrations (the fraction coarser than 0.090 mm.) based on the regression model presented in Fig. 25 are also included on the OBS scale. Cycles in turbidity of 3 to 5 minute period are apparent, as well as a strong positive relation with multi-minute vertical velocities, and negative relation with horizontal velocity cycles.

Could the fluctuations seen in Fig. 26 be spurious; more precisely, could the multi-minute OBS response fluctuations have not been caused by real fluctuations in sand concentrations at the sensor but rather represent fluctuations in OBS calibration error? The answer appears to be no. In section 4.1, the change in OBS output necessary to infer a real change of sand concentration (at 95%) was estimated at some 140 mV, based on 7 s samples. Although low-frequency OBS fluctuations in Fig. 28 are of the order of only 100 mV, they nonetheless probably denote true cycles in sediment concentrations. The residual error levels in the calibration models (Figs. 24, 25) reflect momentary fluctuations in silt/clay/sand proportions within the 7 second-long suspension samples. Such fluctuations in sample composition, and the resultant calibration error levels, are likely to exaggerate uncertainty in comparing longer based averages.

It has also been noted that the calibration errors about the regression line (Fig. 25) do not appear to be correlated with the u or v velocity conditions at the time of sampling, while the OBS fluctuations in Fig. 26 clearly are. Moreover, if any slight correlation of calibration error with velocity conditions existed (but was too weak to be revealed in our sample), such calibration
Fig. 26: Concurrent time series of 1 min means of $U$, $V$ and OBS output, based on 80 minutes of data from June 13, 1988 deployment.
errors would be expected to lead to underestimates of concentrations in conditions of low u, high v, and vice-versa; the proportion of coarser sands in the suspensions, and thus the calibration errors, should be increasing in such conditions of upward flow (leading to underestimates of true concentrations). Thus the real correlations may be somewhat underestimated in Fig. 26. A multi-minute positive correlation between sand concentrations and v velocities appears to be real.

Although a fair degree of "coincidence" of the OBS output and v cycles in Fig. 26 is quite apparent, the absence of a strong proportionality between their amplitudes produces a fairly low correlation coefficient; the coefficient is 0.28 between the OBS and v series (0.31 when both are detrended), and -0.50 between the OBS and u series. The correlation statistic is optimised for linear relations between series; here cycles appear to have a strong coincidence in phase but a weak linearity (proportionality) in amplitude.

Fig. 27 compares in more detail 18 minutes of OBS and v fluctuations, also starting at 17:42 hrs on June 13, 1988. Conspicuous multi-minute cycles in both records are again apparent even in essentially "unfiltered" series (e.g. in the first 10 minutes of the OBS record). Superimposed on 2 s. mean values (dashed) of OBS and v are series that have been low-passed (solid line), with the same digital filter (with half-power at 30 s, cf section 3.4) used in the preceding chapter to extract intense burst-scale motions from background lower frequency fluctuations. The residual series around the solid curves are thus high-passed (hp) "burst-scale" signals with fluctuations of duration typically 5-15 s (cf. Fig. 16).

In addition to the positive correlation of 2-4 minute-scale (solid) cycles of OBS output and v already seen in Fig. 26, shorter period OBS and v cycles in both the low and high-passed series display a degree of positive correlation. Based on 2.2 hours of data the correlation coefficient of high passed OBS is 0.31 with the hp v
Fig. 27: 18 min time series of OBS output and vertical velocities, revealing high-frequency fluctuations (dashed lines) superimposed on lower frequency oscillations (solid lines) in both signals. June 13, 1988 deployment. Events labelled A and B are discussed in the text.
series and -0.32 with the hp u series. Detailed aspects of the higher-frequency links between the OBS and V signals will be further discussed below. For now, it can be concluded that a positive dependency between the OBS and v signals occurred over a wide range of frequencies.

Within a systemic "black box" type of approach to the suspension process, the turbidity signal at 1 m can be simply envisaged as a response to vertical velocity driving forces through this level. An interesting question within such a framework is whether the turbidity fluctuations are more strongly related to the multi-minute flow oscillations or to the higher frequency motions.

A quantitative answer will depend on the form of relation envisaged. Fairly simple spectral methods can give information on the degree of linear relation between two signals (here turbidity and vertical velocity) over their different frequencies. The coherence\(^2\) function (Bendat and Piersol, 1986) between the OBS and v series for the main data run (Fig. 28) measures the degree to which the two signals are related as would be the input and output of a constant parameter linear system. (Two signals in the same frequency band are coherent if they have a constant amplitude and phase relationship. To produce a correlation coefficient of +1 the phase difference also has to be nil. In the absence of extraneous noise linearly related signals would have a coherence squared of unity at all frequencies, while two "unrelated" signals have coherence 0.)

The black box approach depicted above overlooks of course that flow events both upstream and well below the sensor level, and hence not necessarily included in the v signal at the sensor, also influence the sediment content reaching the OBS unit. In this sense, the monitored v signal is one of many inputs driving the suspension "system" and should not be expected to completely determine OBS output. Alternatively, both the OBS and v signals at 1 m may be seen as outputs of a complex system encompassing the whole flow, and driven by infinitesimal instabilities near the bed.
Fig. 28: Coherence² function analyzing the degree of linear relation between OBS output and V fluctuations over different frequencies. Based on 2.2 hrs of records from June 13, 1988.
The coherence statistic displayed in Fig. 28 can nonetheless be used to assess the average degree of coherence, and by implication possible interrelation, of the two signals over their different frequency components. Although based on 2.2 hrs of data (June 13, 1988) this statistic between OBS return and v has a very high degree of random error (Bendat and Piersol, 1986): the standard error for the smooth fit plotted is of the order of 25% of the expected value. Thus it is unclear whether the dip in coherence level for components of approximately 20 s period is significant.

Two conclusions can be drawn from this plot. First, as expected a relation between sand content as output and vertical velocities as driving force can be envisaged although, as coherence is much below 1, it could be only crudely approximated as linear (or, equivalently, other upflow events, uncorrelated with measured v, also drive OBS output). Secondly, the level of association between the two signals appears to be at least as great for the multi-minute flow cycles (f<0.02 Hz) as for the faster turbulent oscillations. These results generally confirm the conclusions drawn above from a comparison of correlation coefficients between multi-minute and burst-scale (multi-second) components of the OBS output and v series.

To summarize, contrary to what might be expected the turbidity fluctuations at the sensors are not completely dominated by higher frequency suspension events: rather these are imbedded in strong concentration cycles tied to multi-minute flow oscillations. These findings will be interpreted next in terms of plausible mechanisms of suspension, and their sediment transport implications assessed.
4.2.2 High frequency turbidity fluctuations: a physical interpretation.

Fig. 27 documented a statistical association between positive (upward) high frequency vertical motions and equally rapid increases in suspended sand contents (and vice-versa). This result fits common expectations. The lack of an exceptionally strong relation between such events is also interesting from a physical (process) sedimentology point of view. The correlation coefficient between high passed (hp) OBS and v series was 0.31. More tellingly, Fig. 27 displayed a number of strong upward motions (e.g. points marked A) that produce only moderate increases in turbidity, and conversely many strong peaks in turbidity (e.g. points marked B) not coincident with particularly energetic upward flow, or even accompanying downward vertical fluctuations. Such discrepancies appear to be too large to simply reflect errors in predicting sand concentrations (of the order of 50 mg/l, section 4.1).

Such a weak degree of association is quite typical in turbulence. A correlation of 0.3 is common between turbulent fluctuations in v and scalar contaminants (e.g. temperature, humidity) in the atmospheric boundary layer (e.g. Phelps and Pond; 1971). The correlation coefficient between high-passed u and v series on the Fraser is itself only of the order of -0.4, and so many turbulent upwelling motions (v>0) are not only relatively poor in sediment but also fail to bring with them the expected deficit in horizontal momentum (u'<0). That such behaviour also affects turbulent suspension is thus not, a priori, surprising.

Within any one flow record, the relation between instantaneous vertical motion and sediment concentration at sensor height is, understandably, extremely complex and predictable only in a statistical sense (as average associations over many eddy motions). The interpretation of sand suspension events based purely on Eulerian (one-point) data that will be attempted here is at least
as uncertain as (and indeed tied to) the visualization of bursting motions from one-point observations. Dispersion of the suspended phase is best understood from a Lagrangian point of view, where fluid parcels are tracked and allowances made for contaminant loads at their origin, and exchanges along the trajectory to any point. For example, although on average the sand content of a parcel of fluid traveling upwards may be enriched relative to its surroundings, its actual content will depend on the recent history of suspension events upstream, as they affect the instantaneous (as opposed to average) concentration where its motion was initiated. Not all upward fluctuations at the sensors correspond to flow parcels directly originating from near the bed, or ejected at a time when near-bed concentrations need have been particularly high. "Sweep" or "inrush" motions \((u' > 0, v' < 0)\) near the bed may temporarily decrease local sand concentrations so that ejections or outward interactions immediately after the sweep might bring up less sediment than average.

A further complication in interpreting the signals results from the submerged weight of suspended sands: contrary to a passive chemical or physical contaminant, for example, sand particles fall out of suspension and do not in general stay long associated with the flow parcels that carry them (cf. the "crossing trajectories effect"; Lumley, 1976; Yudine, 1959). Thus the sand content of a flow parcel crossing the sensor depends not only on the initial concentrations at the origin of its motion but also on the distance traveled and velocity history of the parcel along its trajectory. In particular, ejected sands do not disappear when the forces that led to their suspension are spent, and as they rain down they may even produce turbidity peaks in downward flow parcels.

The high-passed records seen as residuals around the solid lines in Fig. 27 mainly reveal 1-10 m scale eddy motions, those responsible for seconds-scale \(u, v\) fluctuations in flows where mean velocities are of order 1 m/s. It can be argued, heuristically, that eddy motions of this scale that happen to involve at the same time
strong upward flow with strong horizontal deceleration are the ones most likely to originate from the low momentum zones closer to the river bed, and thus likely to carry greater concentrations of suspended sands. The hypothesis appears to be verified based on the 2.3 hours of hp-u, hp-v, hp-OBS data (from June 13, 1988) analysed. For example the mean increment in hp-OBS (high-passed series) during periods when hp-v exceeds +3 cm/s and hp-u is negative (corresponding to an ejection motion) is +40 mV (s.d.=48 mV, N=415), while it is only +10 mV (s.d. =46, N=161) under the same v conditions when hp-u is positive (outward interaction). These means are significantly different at the 1% level.

Fig. 29 presents a smoothed response surface drawn through the highly scattered cloud of hp-OBS, hp-u and hp-v values, associated with every 2 s period in 2.2 hrs of record. As can be clearly seen, a greater deficit in horizontal momentum (hp-u < 0) along with sudden upward flow (hp-v>0) leads to the greatest momentary increase in turbidity (hp-OBS>0). Interestingly, there is an indication that midscale changes in u or v produce the greatest marginal changes in turbidity and that, beyond these, there may be a tapering off of the suspension effect at the 1 m level.

A planar least-squares fit through these observations takes the form:

\[(hp-OBS) = -0.9 + 4.7 (hp-v) - 3.3 (hp-u)\]

and, by adding the (hp-u) variable, the multiple correlation coefficient between (hp-OBS) and flow variables increases from 0.31 to 0.48. As argued above, upward parcels that have a stronger deficit in u velocity (and so are thought more likely to have just originated from near bed) are the ones that statistically tend to bring up higher concentrations to sensor level.
Fig. 29: Smoothed surface of (hp-OBS) responses (in mV) during 2 s periods with various intensity of rapid (turbulent) U and V fluctuations (hp-U' and hp-V') (in cm/s). The latter values are rounded to simplify display. Based on 2.2 hrs of records from June 13, 1988.
In contrast to this simple picture of burst-scale turbulent suspension events, the relation between multi-minute turbidity and flow oscillations (Fig. 26) may require more careful interpretation. The view occasionally taken that these slow disturbances simply reflect turbulence was argued previously to have troublesome implications. The extension of the simple eddy concept, advected at roughly mean flow velocity, to this scale of motion may not be justified. Alternate interpretations would depend on slow fluctuations of mean streamlines at the sensor due to local bed changes (cf section 2.6).

4.3 Recurrence analysis of high suspended sediment concentrations

Before investigating the suspension efficiency of burst-like motions, the recurrence of high sediment concentration "events" at the sensor will be analysed. If intermittent intense concentration events are in operation, information on their recurrence is important. An approach complementary to this analysis of simple high concentration events will be explored in a coming section: there, the recurrence of events characterised by intense sediment flux, vertically through the sensor level, will be studied along lines similar to that of intense momentum exchange events discussed in chapter 3.

A number of problems in analysing the series of OBS returns for high concentration events must be addressed. The first is the inaccuracy and possible bias in the calibration of sediment concentrations, obtained in section 4.1, for extreme values of OBS output. Predicted extreme concentrations are nominal, as such high OBS returns as will be considered in much of this analysis were not accounted for in the calibration samples, and often refer to events lasting much less than the 7 s calibration sampling. Thus actual values of extreme sediment concentration proposed below amount to
strong extrapolations of the available regression model. Based on
the patterns discussed in section 4.1, highly turbid parcels may be
proportionally enriched in sands relative to silts and clays, and
use of the regression models would thus lead to underestimates in
the case of extreme sediment concentrations and fluxes.

It must also be noted that, in principle, return periods
for extreme OBS values may depend considerably on a choice of sensor
cutoff in the frequency domain. While the contributions of
frequencies above 1 Hz (the nominal aliasing filter cutoff in this
study) to velocity spectra and especially momentum exchange are
inherently minor, a complete optical turbidity spectrum might behave
differently. In this study, low-pass filtering of the OBS output in
the field assured that little power occurred above 2 Hz (Fig. 12).
However, an unfiltered OBS unit's inherently high frequency and
wavenumber responses could react to the finer-scale texture of local
concentrations, potentially producing greater instantaneous
variability (as individual passages of sand particles affect the cm
scale sampling volume of the OBS). Two second means of OBS output
were retained in the following recurrence analysis to allow only
OBS cycles longer than 4 s to appear; any fluctuations faster than
this cutoff were thought unlikely to correspond to large scale
bursting motions.

Fig. 30 presents a 100 minute series of smoothed u, v
components from June 13, 1988, along with those peaks in 2 s mean
OBS return that exceed 2100 mv. This is a moderately high turbidity
threshold (cf. Fig. 27), suitable to illustrate the typical pattern
of recurrence of high concentrations. This value of OBS output
nominally corresponds to sand (D>0.09 mm) concentrations of 590
mg/l; it is exceeded only 3.4% of the time in 2.2 hrs of the 2 s
mean OBS series. The high concentration events displayed in Fig. 30
are generally associated with minute-scale periods of high v and low
u in the low-passed velocity series. This association in large part
reflects the fact that under such conditions low-passed OBS returns
are themselves highest (cf. section 4.2.2 and Fig. 26), and so the
Sand concentrations are nominal.

With half-power at T = 30 s, June 13, 1988 deployment.
Records of low-frequency u and v fluctuations (low-passed
transient noise spikes), along with simultaneous
(continuous lines forming spikes), 2 s average OBS

FIG. 30: A 100 min series of OBS events over 2100 mv

Time (min, from 17:42 hr PST)

OBS output (mv)

Conc. of sands

Conc. of sands

over 0.99 mm

over 2100 mv

Output events

2 s average OBS

V (cm/s)

U (cm/s)

75 - 85 - 95 - 105 - 115

10 - 5 - 0

100 2000

0 2200

0 008

0 009

0 010
brief increases in turbidity caused by ejections occur on already high base turbidity levels.

In section 4.2.2, ejections \((hp-u'<0, \ hp-v'>0)\) that contribute strongly to momentum exchange at the sensor were seen to produce large turbidity increases. Nonetheless, Fig. 30 suggests that the timing of strong turbulent ejections does not, of itself, completely determine that of exceptional concentration events. The presence of strong low-frequency turbidity cycles, underlying these higher frequency fluctuations, also clearly affects the recurrence of absolute peaks in sand concentrations at the 1 m level.

4.4 Horizontal and vertical suspended sediment fluxes at sensor level.

The simultaneous concentration and velocity data will now be combined to produce time series of horizontal or vertical suspended sediment fluxes at the sensors. This analysis will allow estimates to be made of the mean fluxes, and more importantly the spectral contribution to these fluxes from motions in the different frequency bands. Following the practice of earlier chapters, time series of instantaneous fluxes will also be analysed for large intermittent contributions. In particular, it will be possible to quantify the efficiency, in terms of vertical sediment transport, of turbulent ejections of various levels of intensity, an important objective of this study.

4.4.1 An analysis of the vertical sediment flux.

The primary process of interest in this study is the vertical mixing of sediments across the sensor height. It is ultimately responsible for maintaining, despite the tendency of the sediment to fall out of suspension, a mean sediment concentration away from the bed, and thus a substantial downstream transport of
sediment along with the flow.

The statistical association seen previously of higher sediment concentrations with upward moving flow parcels, and lower concentrations with downward moving ones, implies prima-facie a net upward flux of sediment through the sensor level. Simultaneous OBS and v data can yield an estimate of this flux. In reality, however, this theoretical "mixing" flux (due to sediment mixing by turbulent or other vertical motions) is reduced or may even be reversed by the tendency of the upward velocities of the sands to be systematically smaller than that of the upwelling flow parcels (and downward velocities higher), the more so the coarser the sediment (the greater its fall velocity). Since only the vertical flow velocities and not the actual particle velocities were monitored, the net effect of the fall velocities must be first assessed, at least approximately, if information on vertical suspension fluxes is to be gained.

It is useful conceptually to separate the net vertical sediment flux into a nominal mixing component, here estimated through the covariance of the OBS and v signals, and a fall velocity component. A similar, although less detailed analysis can be found in Soulsby et al. (1985). In uniform two-dimensional flow (and sediment transport) conditions, the net vertical sediment flux would be nil, the resultant of a mean upward mixing flux and an equal downward sedimentation flux. The latter depends only on the mean sediment concentration and fall velocity at sensor height.

To formalise: if \( C_d \) is the concentration of sands of calibre \( d \) (fall velocity: \( w_d \)) in a flow parcel travelling with a vertical velocity \( v \), then assuming that the vertical acceleration of the parcel is much smaller than \( g \), the sand grain's actual vertical velocity is approximately \( v - w_d \) (Nielsen, 1984). Thus:

\[
(1) \quad C_d(v - w_d)
\]
represents the vertical flux of that sand fraction at that location
and instant. Assuming steady-uniform flow conditions, its long-term
mean vertical flux through the sensor level is:

\[ \overline{C_d} (v-w_d) = 0 \]

(here \( X \) is a long term mean of a series \( X \) at the sensor). It follows
that under such conditions the long term mean concentration of that
fraction above sensor height is constant. Breaking the sand
concentration into its mean and fluctuating parts:

\[ C_d = \overline{C_d} + C_d' \]

one finds that the net vertical flux can be expanded to:

\[
\begin{align*}
(\overline{C_d} + C_d') (v - w_d) &= \overline{C_d} v - \overline{C_d} w_d + C_d' v - C_d' w_d \\
&= \overline{C_d} v - \overline{C_d} w_d
\end{align*}
\]

since \( \overline{v} = \overline{C_d} = 0 \)

Thus for each fraction the net vertical flux is the sum of a mixing
flux due to vertical flow motions (\( \overline{C_d} v \)), and a passive
sedimentation flux (\( \overline{C_d} w_d \)) that on average depends on mean
concentrations at sensor level and fall velocity.

Adding up these net fluxes for all the suspended fractions
indexed by caliber \( d \) one obtains a total flux:

\[
\begin{align*}
\Sigma (\overline{C_d} v) - \Sigma (\overline{C_d} w_d) &= \overline{v} (\Sigma C_d) - (\Sigma \overline{C_d}) w^* \\
\end{align*}
\]

where summations are over size fractions \( d \) and \( w^* \) is a weighted mean
fall velocity:

\[ w^* = (\Sigma \overline{C_d} w_d) / (\Sigma \overline{C_d}) \]
Thus, the overall net vertical flux can be expressed as:

$$\overline{v \, C^*} - \overline{C \, w^*}$$

where $C$ represents total concentration. The total flux over all fractions can thus be again expressed as the difference between a flow driven mixing flux and a passive sedimentation flux.

Since the mean sedimentation flux depends only on mean properties of sediment concentrations and fall velocity, the contributions of the different frequencies of flow motions to the net flux occur through the mixing flux covariance term ($\overline{v \, C^*}$). Further, assuming that the linear regression model for sand concentration as a function of OBS return (denoted "OBS") is exact over the entire observed range of returns (more precisely that its error is uncorrelated with $v$, as appeared to be the case in the study samples, cf. s. 4.1):

$$C = a \, \text{OBS} + b$$

one can estimate this total "mixing flux" by the covariance:

$$\overline{v \, C^*} = a \, \overline{v \, \text{OBS}^*}$$

and the net vertical sediment flux becomes:

$$a \, \overline{v \, \text{OBS}^*} - \overline{C \, w^*}$$

How well do such idealizations fit the study conditions near Mission? The above analysis assumes statistically steady and uniform flow conditions and sensor data averaged over a large number of the longest wavelength bedforms present. Such assumptions do not strictly hold in this study (cf. section 2.4). In such ideal conditions, since the upward mixing flux exactly balances the downward sedimentation flux, the resultant vertical flux is nil and constant mean concentrations occur above sensor height. However the 7 hour time series of OBS output presented in chapter 2 (Fig. 8) reveals multi-hour fluctuations and a possible long term declining trend in concentrations (of the order of 5 mg/l per hr) at sensor
height during the survey. Equation (3) applied to the June 13, 1988 data for the sand fraction \((D > 0.09 \text{ mm})\) predicts a 1 hour mean upward mixing flux of the order of 3 g/m² s, counterbalanced by a substantially bigger downward sedimentation flux of the order of 9 g/m² s. The weighted mean fall velocity \(w^*\) appearing in (3) was computed based on the mean proportions of the different sediment fractions in the sampled suspension at sensor level (section 4.1), using standard curves, adjusted for water temperature, of fall velocities against sediment size for river sediments. The error in this estimate of \(w^*\) cannot be large enough (300%) to account for the imbalance between the two terms of (3).

This imbalance might reflect incipient local sediment deposition, related to the approach of a large bedform. It is interesting to note that Soulsby et al. (1985) also obtained downward net vertical fluxes, using a similar method from sensor data at 17 and 33 cm above the crest of a dune in a tidal flow. These authors interpreted this finding to reflect a streamwise non-uniformity in transport, related to crest advance. Interpreting such a non-zero net flux should be done with caution, however. Lack of equilibrium between the two vertical fluxes in (3) could also occur in stable, neither erosional nor depositional environments, and be due to violations of other assumptions basic to the analysis. Poorly understood deviations from the assumed fall velocities in (1) for sediments within turbulent parcels, or in the OBS calibration implicit in (2) may severely bias this computational method. It is possible, for example, that for many violent vertical motions, contributing significantly to the mixing flux covariance, actual concentrations have been systematically underestimated. Field calibration models for a concentration sensor are necessarily adjusted to moderate, longer duration events. More work appears to be required before the approach embodied in (3) can yield accurate real-time assessments of local aggradation or degradation conditions.
Even where steady/uniform transport conditions are not realised, however, the intensity of the upward mixing flux of sands (2) due to vertical flow motions is a key determinant of the concentration profile: higher fluxes tend to be balanced by the settling of greater sand concentrations above sensor height. The result is higher concentrations away from the bed where horizontal velocities are greater, and so larger suspended sediment transport rates. In this way the processes behind the mixing flux strongly control the amount of suspended sediment transport.

The question next addressed will thus be: what are the relative contributions of faster burst-like motions and multi-minute flow oscillations to the net mixing flux 1 m from the bed? To answer this question, the OBS and v time series will be analysed spectrally for the frequency contributions to the mixing covariance term (2). Because of uncertainties just mentioned in the validity of assumptions leading to (2), the results can be taken only as indications of the relative importance of these processes.

4.4.2 The frequency contributions to the net vertical mixing flux.

Fig. 31 presents a cospectrum of OBS output and the vertical velocity component. It shows the contributions to the mixing flux (2) of the two signals from different frequency bands. The area-preserving plot is based on 2.3 hours of data on June 13, 1988, and estimates were smoothed to a frequency resolution of 0.0049 Hz. The whole spectrum accounts for the mean covariance of 23, 13.6 min long (212 points) time segments (each detrended and tapered). Because of the weak coherence between the two signals (coherence squared is of the order of 0.1, Fig. 30) these smoothed cospectral estimates are affected by relatively high random error; the standard error of estimate here is of the order of 25% of the estimate.
Figure 31: OBS, v cospectrum based on 2.2 hrs of records from June 13, 1988.
The contribution of flow fluctuations longer than approximately 1 minute to the total vertical sediment flux integrates to approximately 30% of the total, based on the area under the cospectrum. This result is of the same order as the contribution to momentum exchange of flow cycles longer than 1 min (section 3.1). The cospectral analysis thus quantifies the observation made previously that sediment suspension at the 1 m level, rather than being completely dominated by burst-scale turbulent effects, is in important measure also driven by multi-minute flow perturbations. The river sedimentologist surprised by this result should again bear in mind that large low frequency contributions to vertical contaminant fluxes such as temperature or humidity are not unusual in the turbulent boundary layer over the ocean (e.g. Pond et al, 1971; in our data, T= 1 min corresponds to n = 0.017). The cospectral peak near f=0.1 Hz nonetheless indicates that 10 s scale turbulent events dominate the overall mean sediment flux, as they did the momentum flux analysed in the previous chapter (Fig. 15).

4.4.3 Intermittent high sediment flux events.

As was done in the previous chapter with momentum exchange, it is possible to isolate for analysis burst-scale vertical sediment flux events embedded within the multi-minute flow oscillations. These events are distinct from the simple high sediment concentration events previously analysed in section 4.3; their identification involves both OBS and v data. Fig. 32 presents a time series of high-passed (hp; cutoff at T= 30 s) contributions to the vertical "mixing flux" <OBS'\*v'> from June 13, 1988. Also displayed for comparison are the low-frequency (low-passed: lp) vertical
Fig. 32: A 22 min series of high-frequency contributions to vertical sediment mixing (hp-OBS*hp-V') and momentum exchange (hp-U' * hp-V'). Along with low frequency fluctuations, 'E' and 'I' denote ejections and inrushes, respectively, bringing up sediment-rich and sediment-poor flow parcels across the sensor level.
velocity fluctuations and the simultaneous turbulent (hp) momentum exchange series.

While major momentum events are labelled as either ejections (E: $u'<0, v>0$) or inrushes (I: $u'>0, v<0$), two kinds of burst-scale events strongly contribute to enrichment in sediment of the flow above sensor level. These will be named positive type (when high concentrations go upward) or negative type events (when low concentration flow parcels are brought down out of the upper flow).

Although the correspondence between ejections and positive events, or inrushes and negative, is fairly good the relative contribution of a given event to either flux does not strictly match. Possible reasons for this were given in a previous section: a moderate ejection in terms of momentum exchange (e.g. at 4.1 min) could for example originate from, or pass through, an area that happens to be quite enriched in sediment due to upstream events, and so contribute in a major way to sediment mixing.

This effect can also be observed in Fig. 33, which contrasts the sediment and momentum mixing contributions of individual 2 s periods during ejections. For these events, the correlation coefficient between the two flux contributions is 0.45, based on 2.2 hrs of data, and very strong sediment mixing can be associated with fairly weak events in terms of stress. The true level of correlation is again degraded somewhat by the existence of random errors in relating instantaneous OBS values to suspended concentrations. Despite this lack of correspondence between the two kinds of fluxes, which may also be related to the trajectory crossing effect discussed in section 4.2.2, major periods of activity in Fig. 36 nonetheless coincide in each series.

An indication of how effective occasional strong ejections are in maintaining suspension levels is given by a compilation of their aggregate contribution to the high-frequency part of the "mixing" flux (hp-OBS*hp-v) (which here is 40% of the total mixing flux when all frequencies are included). Fig. 34 presents a ranking
Fig. 33: Scatter plot comparing the high-frequency stress bearing and sediment mixing efficiencies of individual 2 s periods chosen during turbulent ejections. Based on 2.2 hrs of records from June 13, 1988.
Fig. 34: Aggregate duration as well as percentages of the high-frequency contributions to both momentum and vertical sediment fluxes associated with ejection periods exceeding various thresholds of \((hp-U' \times hp-V')\). 2.2 hrs of records, June 13, 1988 deployment.
of ejections, by threshold high-passed kinematic stress exceeded, and their aggregate contribution to (hp) momentum and sediment exchange for the 2.2 hr main study run. Intermittency in sediment suspension is in evidence. Those ejections exceeding -45 cm$^2$/s$^2$, for example, occupy only 1% of the total time, yet contribute 16% of the (hp) momentum exchange and 6% of the (hp) sediment mixing.

These comparisons of course only bear on the high frequency flux components. Are burst-scale "events" negligible however when assessed against the overall momentum and sediment fluxes, all frequencies combined? The answer, interestingly, is no. It will be seen that the intermittency is essentially contained within these high-passed signals. Fig. 35 presents the same analysis as done on the high-passed flux records, but this time based on 2.2 hrs of the unfiltered $u'v'$ and OBS$v'$ flux records. Ejection events exceeding various extreme ($u'v'$) thresholds were selected and their contribution to the overall fluxes assessed. The results can be seen to be very similar to those computed from the high-passed records (Fig. 34). The top 1% of ejection events now produce 10% of the stress and 7% of the sediment mixing.

The extraction of turbulent components with periods shorter than some 30 s (the filter half-power point), seen in Figs. 32, only allows the brief intermittent flux "events" to stand out more clearly than if they were imbedded within the lower frequency contributions. While the filter cuts down on the stress level associated with any event, Figs. 34 and 35 show that it does not substantially distort their relative contribution to the mean flux. This property of the 30 s filter was general in our analysis. The "intermittency preserving" effect of the filter could also be graphically assessed in chapter 3 when stress events were plotted before (Fig. 16) and after (Fig. 22) high-pass filtering.

In Figs. 34 and 35, ejection events selected for their large contribution to momentum flux are seen to be important to sediment mixing, though not generally quite as efficient in this latter respect. The true degree of intermittency of high-passed
Fig. 35: Aggregate duration as well as percentages of the total (all frequencies) contributions to both momentum and vertical sediment fluxes associated with ejection periods exceeding various thresholds of \((U' \cdot V')\). 2.2 hrs of records, June 13, 1988 deployment.
vertical sediment mixing is much greater than illustrated in that figure, when all sudden vertical motions throwing up sediment are tallied, irrespective of their contribution to stress. Fig. 36 displays an analysis of all "positive mixing events" (in the sense of Fig. 32) ranked by size of contribution to (hp) sediment mixing, in terms of aggregate duration and suspension work. In this ranking events exceeding some 540 mV cm/s of flux occupy, as above, 1% of the record, yet contribute 20% instead of 6% of the high-passed component of vertical suspension flux. (The top 1% of events in the unfiltered series similarly produce 18% of the total sediment flux). The largest 5% of (hp) events (by duration), exceeding 250 mV cm/s, contribute 40% of the (hp) suspension flux (the contribution is 45% in the unfiltered series).

Such intermittence of sediment fluxes was not present only in the June 13, 1988 conditions. Fig. 37 superimposes the percentage contribution to sediment flux against total duration of large positive events for both the June 13 and June 8, 1988 data runs near Mission (cf. section 2.4). In both deployment conditions, events exceeded only some 1% of the time cause around 20% of the total suspension.

Fig. 38 presents average recurrence periods for high-frequency positive mixing events of various intensities, for the June 13, 1988 data. The largest 5% of events just mentioned (exceeding 250 mV cm/s in the hp series and producing 40% of the flux) recur approximately every minute on average; on the other hand, events exceeding ten times the mean high passed mixing flux (550 mV cm/s) and contributing some 20% of aggregate flux, would recur on average every 3 minutes. Fig. 39 superimposes the recurrence periods for large positive events for June 13 and 8 study conditions. To permit comparison, large positive mixing events have been normalised by the average value of mixing activity applicable in each environment.
Fig. 36: Aggregate duration as well as percentage of (hp) vertical sediment flux associated with periods when (hp-OBS*hp-V') exceeded various threshold values. Sand fluxes are nominal. 2.2 hrs of records from June 13, 1988.
Fig. 37: Superimposed curves of percent of sediment flux accomplished in percent time for 2 different deployment conditions. Details of flow conditions in each deployment are given in section 2.4.
Mean time between susp. events exceeding $(hp-\text{OBS} \times hp-V')$ thresholds.

Fig. 38: Mean recurrence periods between "positive" turbulent mixing events (defined in the text) exceeding various thresholds of $(hp-\text{OBS} \times hp-V')$. Based on 2.2 hrs of records from June 13, 1988 deployment. Sand fluxes are nominal.
Mean time between susp. events exceeding normalised flux thresholds

Mission, 06.13.88, 134 min
$D = 10 \text{ m}; V_s = 1.4 \text{ m/s}$

Mission, 06.08.88, 35 min
$D = 8 \text{ m}; V_s = 1.1 \text{ m/s}$

Fig. 39: Superimposed curves of recurrence periods between "positive" turbulent mixing events for two different deployments. Details of flow conditions in each deployment are given in section 2.4. The threshold flux levels on the abscissa are normalised by mean flux during each deployment.
The conclusions of the recurrence analysis (Figs. 38, 39) are two-fold: as in the analysis of stress "events" (Fig. 20), there is a fair coincidence between the curves from different flow conditions. There may thus be, as can be expected, some general statistical law at work relating the number (hence recurrence period) of extreme turbulent flux events to their relative size. Clearly, many more deployments over a far wider range of flow conditions than were encountered on the Fraser River need to be carried out to establish any such relation and define the parameters affecting it. What is clear however from Figs. 20 and 39 is that in neither case is there an obvious single time scale, describing the recurrence of a single class of dominant stress or suspension "events". In this sense, the view that a predictable mean burst period (given for example by the conventional outer flow scaling) is of immediate practical use in understanding and quantifying suspension is put into doubt.

4.4.4 Resultant downstream suspended sediment transport.

The resultant mean downstream suspended sand flux q (D>0.09 mm) at sensor level on June 13, 1988 is given by the mean product of instantaneous concentration and horizontal velocity, estimated below:

\[ q = (a \text{OBS} + b) \bar{u} - a \text{OBS} \bar{u} + b \overline{u} - 345 \text{ g/m}^2 \text{s} \]

It is noteworthy that the \((\text{OBS} \bar{u})\) product is dominated by the mean values of the two variables:

\[ \text{OBS} \bar{u} = \text{OBS} \bar{u} + \text{OBS} \bar{u}' = (180400 - 600) \text{ mV cm/s} \]

The small negative covariance term \((\text{OBS} \bar{u}')\) reflects the repeatedly noted tendency of the faster horizontal flow to be associated with somewhat smaller sediment concentrations. The correction term is
seen to be negligible (0.3% of the total), however. This negative correction term was also reported to be negligible in Soulsby et al.'s (1985) study.

Thus, the mean downstream flux can be essentially expressed as:

\[ q - a \overline{(OBS \ u)} + b \overline{u} = (a \overline{OBS} + b) \overline{u} \]

so that over the 2.2 hrs studied, the suspended load is quite accurately determined by the product of the mean concentration maintained by the vertical mixing and the mean downstream flow at sensor level.

The existence, documented all through this study, of strong multi-minute oscillations in both concentration levels and horizontal velocities at 1 m from the bed implies, however, that repeated sampling over long periods is necessary to assess either of these mean values accurately. Typical hydrometric procedures to assess sediment transport near the bed of a sand river are often based on only a few repeat 30 to 120 s samples of point concentrations and horizontal velocity. The Mission data suggest that relatively inaccurate assessments of the important horizontal flux at such a level may be expected from these procedures. For example, if one 30 s long simultaneous observation of average concentration and average velocity was used to estimate long term horizontal flux, there is approximately a 1 in 5 chance that the result would be in error by more than 20% (based on the statistics of the \( lp-OBS*lp-u \) series at Mission). The sampling error in this case results not from the correlation of concentration and \( u \), but simply from the substantial error in estimating either mean from only 30 s samples.
CHAPTER 5  CONCLUSIONS

5.1 Summary of research question.

As discussed in the introduction, previous work on burst-like motions in large-scale flows has mostly been conducted in benthic and tidal boundary layers. The underlying motivation for the Fraser River study was to begin to investigate the relevance of conventional burst concepts (as put forth in Jackson, 1976 or Allen, 1985) in an explicitly fluvial context, in particular with regard to sediment suspension. The main practical difficulties in such a study are maintaining a stable sensor deployment during high flow conditions, as well as persistent signal corruption problems due to fouling of the sensors by large suspended organic materials. As only minimal prior work existed to guide the investigation, a number of issues were explored. Attention was thus given all along to the frequency content of stress and suspension processes 1 m off the river bed in the Fraser River; in particular the relative importance of multi-minute flow oscillations in these matters was pointed out. The key aims of the study however were to investigate the very existence of identifiable "burst-like" \( (u'v') \) events (defined in section 1.1) and also to test the relevance of the outer flow scaling for burst recurrence, originally established over flat walls in the laboratory, in a much higher Reynolds number fluvial boundary layer, and with the complex wall geometry of active bedforms. Available data allow only speculation on the relation of "burst-like" \( (u'v') \) events in the study environment to "classic" turbulent bursting, however. These issues were discussed in chapter 3, and the main findings will be summarised below under the heading of Momentum Exchange.
It has also been noted in chapter 1 that measurement of turbulent suspension time series has only very recently begun to be carried out, and no analysis has been accomplished to date of the actual contribution of strong stress-bearing "burst-like" episodes to total vertical suspension fluxes. Carrying out such an analysis was a central objective of this study. Whatever their relation to classic bursting, intense burst-like motions have been assumed by many to play a major role in alluvial sediment transport. These and subsidiary issues, discussed in chapter 4, are summarised below under the heading of Sediment Suspension.

5.1.1 Momentum exchange: main findings

**OBJECTIVE 1** was to investigate the relevance of "classic" bursting event definitions and their return period scaling in the field environment.

Quadrant analysis of the \((u'v')\) series clearly reveals intermittent but intense ejection \((u'<0, v'>0)\) and inrush \((u'>0, v'<0)\) events (section 3.2.1, Fig. 16), conventionally taken as indicators of boundary layer bursting episodes. Energetic events occupying only 12% of the record accounted for as much as 80% of the total momentum exchange (Fig. 17).

Difficulties were encountered in objectively defining and counting burst "events" in the fluvial environment. Perusal of the literature suggests that this is a common problem in studies of burst recurrence based on one-point \((u'v')\) records. As usual, event recurrence periods appear highly sensitive to threshold settings, while objective and uniform criteria to set such event-defining thresholds have not become widespread (section 3.2.2, Figs. 19, 20). Based on the Willmarth and Lu (1974) threshold criterion, the recurrence period for burst-like events in the study data is of the
order of 8 minutes, and so much greater than the 20 to 50 s predicted by conventional outer flow scaling (Rao et al., 1971) for this environment (s. 3.2.2). In any case, for practical purposes it may be more useful to acknowledge the continuous distribution of recurrence periods for extreme flux events of varying magnitude.

The inferred dimensions (5-10 s event durations * 1 m/s = 5-10 m) of these burst-like events make them significantly larger than would be pure eddy shedding structures generated at the lee of the largest dunes present (heights - 1 m). Unless one assumes that turbulent bursting is somehow completely repressed in large river flows, it may be assumed that it underlies at least some of these intense (u'v') events on the Fraser River (s. 3.3). A tentative identification of bursting events in the study data is thus based on the intermittency of (u'v') contributions to momentum exchange, rather than on conformity to burst recurrence scaling from laboratory flows.

It is speculated that the spatial variability of shear and downstream pressure gradient conditions near the dune covered Fraser River bed might invalidate the conventional burst recurrence scaling established in more uniform laboratory flows. In particular, it is argued that bursting activity at a fixed sensor should be modulated in time, in response to the advance of active bedforms (section 3.3). Difficulties in tracking location and movement of the smaller scale bedwaves underneath the sensor in the study environment precluded however a testing these ideas.

A more detailed understanding of the link between burst-like (u'v') events, monitored at an appreciable distance from a dune covered river bed, and conventional laboratory bursting structures may require the development of sensor arrangements allowing fuller flow visualization, and bedform monitoring, in fluvial boundary layers.
5.1.2 Sediment suspension: main findings.

OBJECTIVE 2 concerned clarifying the importance of the burst-like stress events, discussed under Objective 1, in terms of sediment suspension.

Conditional analysis of the concentration and velocity time series produces original insights into the suspension efficiency of burst-like motions in the study context. The data indicate that intense burst-like ejection/inrush motions are indeed important in vertically mixing sediments across the 1 m level in the flow. For example, very intense ejection motions with \((u'v')\) values exceeded only 1% of the time, and contributing some 10% to mean turbulent momentum flux, appear to produce 6% of total vertical sediment flux (s. 4.4.3; Figs. 32, 34, 35). Intense burst-like "ejection" events do not completely dominate the suspension process, however, in the study environment. Two effects appear to limit somewhat the relative importance of the intense (ejection/inrush) stress events to sediment suspension at 1 m from the bed.

First, although burst-like motions that contribute significantly to momentum exchange are quite effective in sediment mixing, the statistical association between the momentum and sediment mixing efficiencies of any given motion appears only moderately strong. Very intense suspension fluxes are often attributable to rather "weak" ejections (in terms of stress) (section 4.4.3, Figs 32, 33). These differences may in part reflect the "crossing trajectories effect", which expresses the divergence of the trajectories of flow parcels and sediment grains over any length of time. The complex relation between sediment and water trajectories due to particle settling may weaken the coupling between the vertical mixing of momentum and sediment. A weak degree of correlation between flow velocities and even passive contaminant contents, unaffected by fall velocities, is quite typical in
turbulent mixing, however.

Secondly, strong multi-minute flow oscillations significantly assist the burst-scale turbulent motions in vertical sediment mixing (cf. Fig. 26). The long-period (T>1.5 min) flow oscillations may be associated with some one-third of the total upward vertical sediment flux, based on the v-OBS output cospectrum from June 13, 1988 (section 4.4.2 and Fig. 31).

In any case, turbulent sediment suspension, like momentum exchange, is highly intermittent. After selecting events only for suspension efficiency, the largest ones, occupying only 5% of the time, contribute 40% of the turbulent sediment flux (section 4.4.3, Figs. 36, 37). As with momentum exchange, there is no indication that the conventional scaling of burst recurrence corresponds to the return of any distinctive event level for suspension (Figs. 38, 39). A continuous distribution of recurrence periods for extreme flux events of varying magnitude is again observed.

5.2 Further implications of the findings and avenues for research.

It was seen that the Fraser River observations are compatible with (but do not clearly establish) the operation of turbulent bursting, albeit with mean recurrence periods which appear to differ from laboratory results. An important but difficult set of observations still to be conducted involves multi-point tracking of burst-like motions and ejected suspended sediment plumes through the flow column. Such observations would further clarify, for large-scale geophysical flows, the "bursting conjecture" linking surface boil activity, large motions in the outer flow and near-bed flow instabilities (e.g. Jackson, 1976). There is also a pressing need to develop better sensors and statistical calibration models to monitor instantaneous suspended concentrations in the field environment. A more accurate assessment of the turbulent suspension
process appears to depend on such developments.

The scale of multi-minute flow oscillations at the sensor level and their importance to sediment mixing in river flows were unforeseen, and suggest that the nature of these oscillations be further clarified. The tentative hypothesis, formulated in section 2.6, that the passage of small bedforms under the sensors may partly be responsible (through associated streamline perturbations) for some of the multi-minute flow oscillations in the records would need to be pursued. At least in deep and fast flows, investigating this hypothesis would appear to require the development of portable forward-looking sonar apparatus. It may be possible to investigate a similar effect in much shallower streams, where the progression of small bedforms can be more easily monitored.

In section 3.3, the theoretical possibility of a modulation of burst activity over different parts of fluvial bedforms was discussed. By monitoring the flow at different elevations over sinusoidal wavefields in the laboratory flume it should be possible to investigate the existence of any spatial modulation of burst and suspension activity, its phase relation to the bedform profile, as well as its dependence on bedform steepness, flow separation, etc. If modulation is in effect, its consequences for traditional burst recurrence scaling at one point over natural active dunes could also be investigated in different conditions of flow and bedform translation.

Based on the findings listed above, it does appear that turbulent mixing of both momentum and sediment over a typical sandy river bed is dominated by intermittent, intense events. However, the easy extrapolation of intermittent "bursting" concepts and structural constants from small-scale laboratory flows to the larger fluvial environment may be misleading. Furthermore, the momentum-bearing cores of large burst-like events do not appear to be the only significant contributors to sediment suspension; weaker peripheral motions may also be able to efficiently project sandy flow parcels further out into the flow.
The insights gained in this study clearly do not point to any easy breakthroughs in predicting suspended sediment transport based on the burst concept. A substantial fraction of turbulent suspension away from the sediment surface, in the zone where downstream transport is most important, appears to involve motions, of both long and short timescales, not tied directly to the strong burst-like events. The steps likely required to establish transport models based on bursting events are in any case truly formidable: these would include better parameterising mean burst recurrence as a function of flow conditions over bedforms, as well as investigating the distribution of burst intensities and the controls on the suspension effectiveness of bursts. Indeed, if there is a feedback between bedform development and burst location, timing and intensity, then bursting must, in any case, be seen less as an invariant building block of the turbulence, useful in predicting two-phase flow, than as a link in the coupling of turbulent flow to the deformable boundary.
REFERENCES


