

Hudson Dye Experiment (HUDEX)

This project is a collaboration between Robert Chant of Rutgers University, Rocky Geyer of Woods Hole and Robert Houghton of Lamont-Doherty. The project “Lagrangian observations of secondary circulation and mixing in a stratified channel” involved field work in the Hudson River Estuary that consisted of dye studies, ship board surveys and moored instrumentation. We conducted a pilot study in May of 2001 and the main field effort in the spring of 2002. During years 2003 and 2004 we devoted our efforts on this project to the analysis and write up of the results. Currently there are 3 manuscripts in preparation, and we anticipate a beginning a fourth manuscript later this year.

Field Work 2001

In May 23, 2001 we injected 39 kg of dye into the bottom mixed layer of the Hudson River estuary during flood. The injection occurred approximately 20 km north of the Battery and 2km north of the George Washington Bridge. Shipboard ADCP data from the time of injection revealed a mid-depth maximum in along channel current speed and a lateral circulation characterized by bottom and surface currents flowing to the western flank at 10-20 cm/s and currents in halocline flowing 10-20 cm/s to the east. The first realization of the dye patch at the end of flood confirmed the ADCP observations and revealed that the dye was advected upstream with the flood and across the channel where it was jammed beneath the halocline

During the flood the dye approximately 2 psu although the details of this freshening was not resolved in detail (in contrast during the 2002 field effort this was resolved) The dye remained decidedly in the bottom mixed layer and was capped by the halocline. This observation is consistent with freshening of the dye and of the bottom mixed layer by entrainment of fresher fluid into a turbulent bottom boundary layer.

Three realizations of the patch were observed during the ebb. During ebb there was a tendency for the dye patch to move back towards the deeper channel. However, the dye that was furthest on the shoaling western flank of the channel was mixed vertically during the ebb. This produced a rapid freshening of the dye on the flank. In contrast, freshening of the dye in the deeper thalweg freshened at a significantly slower rate. The most rapid freshening of the dye occurred during maximum ebb.

One surprising result of the field effort is a large discrepancy between the observed spread of the dye and inferred estimates of dispersion based the salt field. Estimates of horizontal dispersion of the dye patch on May 23 was about $100 \text{ m}^2/\text{s}$, and most of this dispersion occurred during a two hour period around maximum ebb. This dispersion rate is ten times less than one inferred assuming a steady state balance between the seaward advection of the salt field by the mean river flow and land ward dispersion.

Results from this experiment suggested a strong interaction between secondary circulation and mixing. However, the 2002 field effort—which included 4 injections and covered more parameter space—clearly indicated that the results from the 2001 field

work would by themselves, over-emphasize the importance enhanced mixing on the channel lateral boundaries.

Field Work 2002

The May 2002 experiment was executed as outlined in the proposal—with the exception that mooring array was significantly augmented from that described in the proposal. The May 2002 study featured 4 dye experiments that bracketed the neap/spring cycle (Figure 1). The first two experiments occurred during neap tides when tidally mean surface to bottom salinity stratification approached 15 psu. The third injection occurred during the neap to spring transition. Stratification was 10-15 psu at the beginning of the third experiment and decreased to 2-3 psu by the end of the experiment. The final injection occurred at spring tide and stratification was weak but slowly increasing. All experiments commenced with an injection of fluorescene dye into the bottom layer and tracked with two boats as described in the proposal.

The mooring array consisted of 4 bottom mounted ADCP's, 12 CT sensors, 2 pressure sensors and an undulating CTD that profiled hourly at site 2 for the first half of the deployment and at site 4 during the second half of the deployment (figure 2). The mooring array was located approximately 3 km north of the George Washington Bridge and site of each dye injection was selected so that during the first ebb the dye patch would advect past the mooring array. The array was deployed on April 22nd and recovered on June 3rd. Figure 3 shows the location of the mooring array and sites of the four dye injections. Current meter data from the array was processed into 15 minute averages for the current meter data and 5 minute averages for the salinity, pressure and temperature data. Additionally, twice during the month cross channel sections were repeated every 15 minutes for one tidal cycle to resolve details of the cross channel structure and estimate fluxes of salt and water. From these sections the mean flow is resolved and showing a classic two-layer system with significant spring neap variability (Figure 4).

During the first dye experiment in 2002 the dye remained in a coherent patch in the bottom mixed layer and moved up-estuary at approximately 5 cm/s over the duration of the 4 day experiment. This upstream motion was consistent with the upstream advection of stratified fluid during the course of the experiment as the estuary became more stratified during neap tide conditions (figure 5).

In contrast, the upstream motion of the dye was significantly reduced following the neap/spring transition that occurred during the third experiment when the dye patch was observed to move up-estuary at a rate of only 1 cm/s. Vertical mixing of the dye patch was even more rapid following the fourth injection and the dye patch was transported seaward after it was vertically advected over a frontal system that develops during the ebb down stream of a channel constriction south of the George Washington Bridge. As

the river began to re-stratify following maximum spring tides this mixed water remains in the surface layer and is eventually transported out of the estuary.

On the first three experiments, when the river was stratified, the freshening of the dye was more rapid on the flood than during the ebb. During neap tides the freshening of the dye was three times more rapid on flood, than on ebb (figure 6). The reduced mixing during the ebb on neap tides allows the river to become strongly stratified by tidal straining and, despite the strong mixing on flood, the estuary remains stratified throughout the tidal cycle. The mixing on flood occurs due to entrainment into the bottom mixed layer that is capped by a strong halocline and contains a mid-depth velocity maximum that tends to advect dense saline water over the bottom mixed layer and promote mixing. The mixing occurs at the base of the sub-surface velocity maximum where Richardson numbers are between 0.25 and 1 (Figure 7). The velocity maximum appears to conveniently define the top of the bottom boundary layer on flood.

While mixing remains strong on the flood tide during the neap-spring transition that followed the third experiment, the freshening of the bottom boundary layer was nearly equal on flood and ebb figure 8. The enhanced mixing on the ebb appears to occur because bottom shear stress is sufficient for a 4-5 thick bottom boundary layer to develop where Richardson numbers are below 1/4. (Figure 9). With mixing active across the main halocline on both flood and ebb stratification breaks down the estuary transitions to its spring-tide conditions.

Summary of Results

In Chant et al (in prep) elucidated bottom boundary layer mixing processes, their rates and variability over the tidal and fortnightly timescales are described. They show that large tidal period asymmetries in vertical salt flux occurred during neap tide with increased salt flux occurring on flood. However, approaching spring-tide the tidal asymmetry in salt flux diminishes. During both neap and spring tide the bottom boundary layer penetrate into a highly stratified halocline just beneath a sub-surface velocity maximum. Salt flux estimates are similar to those obtained by microstructure estimates also made in the Hudson River Peters and Bokhorst (2000). Boundary layer growth is driven by entrainment rather than a horizontal flow convergence. The boundary layer growth rate is consistent with the entrainment model of Trowbridge (1992) when driven with a parameterization for the local bottom stress Trowbridge *et al.* (1999). However, the model over predicts boundary layer growth rates when driven with a parameterization for the effective bottom stress Geyer *et al.* (2000). During highly stratified conditions the freshening of the bottom boundary layer due to entrainment on flood is so rapid that it significantly reduces tidal period salinity excursions to approximately 1/2 the tidal excursion and allows the dye to rapidly move through salinity space.

During ebb boundary layer thickness is consistent with a scaling whereby buoyancy flux associated with tidal straining is balanced by bottom generated turbulence (Stacey, in press). As the ebb boundary layer grows approaching spring tides it extends

into the strong halocline aloft and onto the flank where increased bottom velocities further augment ebb tide boundary layer mixing. With mixing active across the halocline throughout the tidal cycle stratification, is destroyed and the estuary transitions to its spring-tide mixed conditions.

A paper in prep by Lerczak et al discusses salt flux estimates made with the moored instrumentation and ship-board surveys, and compare these with estimates of the estuarine salt inventory. This paper represents the most detailed estimate of salt flux probably ever made in the marine environment. They find significant time-dependency to the salt balance, with a loss of salt during spring tide conditions and a net gain of salt during neap tides. They also find that the dominant salt-flux balance is between the time dependent term, seaward salt flux associated with the mean river flow and landward flux associated with the estuarine exchange. Salt flux associated with tidal pumping is very small. Furthermore, salt flux oscillations are clearly driven by meteorological forcing however these are not apparent in the baroclinic estuarine mode.

The third paper by Geyer et al provides a quantitative assessment of horizontal dispersion and mixing based on the dye experiments. During neap tides, vertical mixing was weak, and the dye patch remained in the bottom boundary layer for multiple tidal cycles. The patch moved progressively landward, decreasing in salinity with time as lower salinity water was entrained into the boundary layer. The patch extended to the landward limit of the salinity intrusion before being transported into the upper layer. Similar conditions were observed until the neap-to-spring transition, during which vertical mixing caused the dye patch to extend to the water surface.

Horizontal dispersion of the dye patch was observed at a rate of 40-120 m²/s, which is significantly higher than typical rates observed in coastal waters, due to the large shears in the estuary. However these rates are much lower than the overall dispersion due to the estuarine circulation, which exceeds 2,000 m²/s during neap tides. The much lower dispersion rate of the dye is explained by its confinement to the lower layer, thus the estuarine circulation results mainly in advection rather than dispersion of the patch.

Lateral dispersion is much slower than along-estuary dispersion, due to the relatively small magnitude of transverse shears. The effective timescale of transverse mixing is approximately one tidal cycle.

Results from this project have been reported at the following meetings:

Physics of estuarine and coastal systems (PECS) meeting Yukatan Mexico. “Secondary flows and lateral mixing processes during ebb tides in a stratified channel ” October 2005. Rocky Geyer, James Lerczak and Robert Chant

Physics of estuarine and coastal systems (PECS) meeting Yukatan Mexico. “Estimates of dispersion in a partially stratified estuary” October 2005. Robert Chant, Rocky Geyer, Robert Houghton, Elias Hunter and James Lerczak.

Ocean Science Meeting, January 2004, Portland Oregon, ““Lagrangian observations on spring to neap variations in tidal asymmetries of mixing and dispersion in a stratified estuary”. Robert Chant, Rocky Geyer, Robert Houghton, Elias Hunter and James Lerczak.

Estuarine Research Foundation Meeting Seattle Washington September 2003, ““Lagrangian observations on spring to neap variations in tidal asymmetries of mixing and dispersion in a stratified estuary” Robert Chant, Rocky Geyer, Robert Houghton, Elias Hunter and James Lerczak.

Estuarine Research Foundation Meeting Seattle Washington September 2003, “Mechanisms driving the time-dependent salt flux in a partially stratified estuary”. James A. Lerczak, Rocky Geyer and Robert Chant.

American Geophysical Union meeting Fall 2003, San Francisco. “Lagrangian observations on spring to neap variations in tidal asymmetries of mixing and dispersion in a stratified estuary” Robert Chant, Rocky Geyer, Robert Houghton, Elias Hunter and James Lerczak.

Ocean Science Meeting. “Direct Observations of estuarine dispersion: Results from a recent dye study” Rocky Geyer, Robert Houghton, Robert Chant. Honolulu Hawaii, February, 2002.

Manuscripts Submitted

Lerczak, J., W.R. Geyer and **R.J. Chant** Mechanisms driving the time-dependent salt flux in a partially stratified estuary. Submitted to the Journal of Physical Oceanography, November 2004.

Manuscripts in Preparation

Chant, R.J., W.R. Geyer, R.H Houghton, E. Hunter and J. Lerczak, “Tidal straining and tidally asymmetric mixing in an estuarine bottom boundary layer: observations with a dye tracer” To be submitted to the Journal of Physical Oceanography

W.R. Geyer, **R. Chant**, R. Houghton, E. Hunter and J. Lerczak Horizontal dispersion and mixing in a partially mixed estuary: results of the Hudson Estuary dye study.

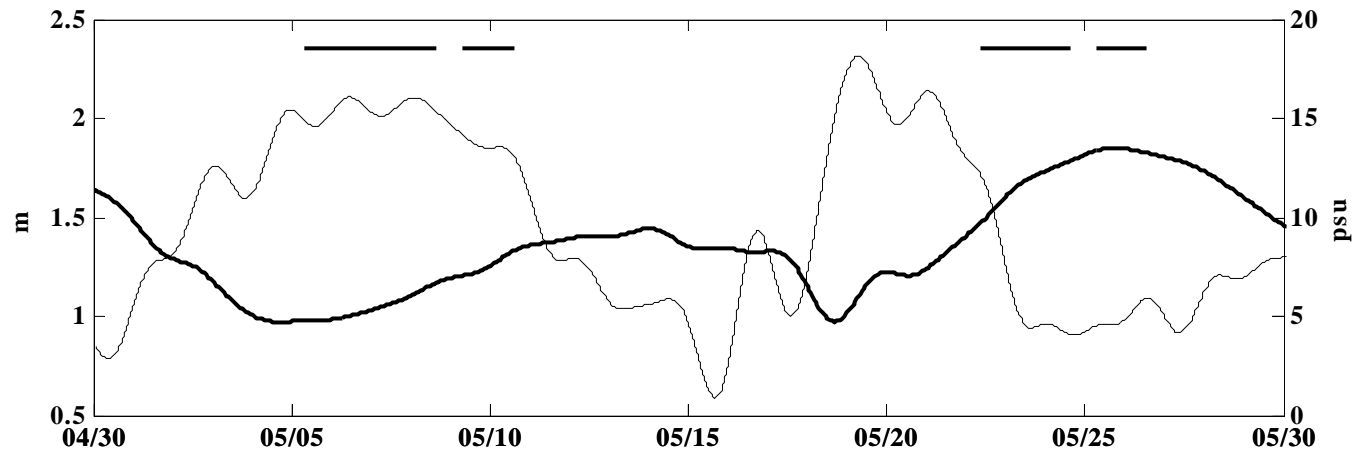


Figure 1. Tidal range at the Battery (Thick line) and tidally mean surface to bottom salinity difference From mooring 4. Thick grey lines at top of figure show duration of each of the four dye experiments.

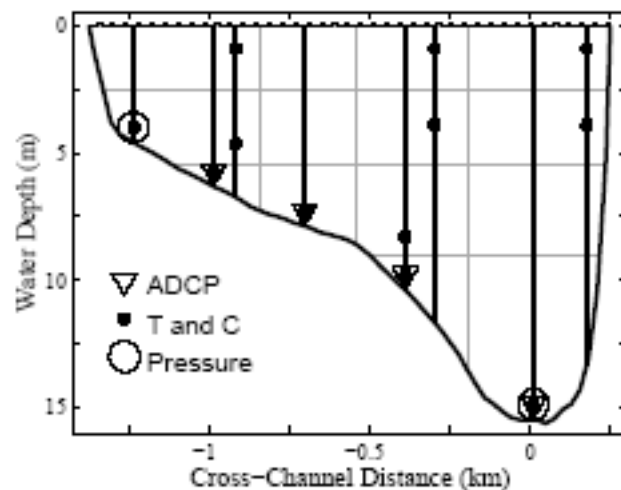


Figure 2: Cross-sectional profile of the Hudson River at the location of the cross-channel mooring array showing the locations of moorings and instruments. The gray lines mark the borders of the 14 regions used to decompose the salt flux. The western side of the channel is on the left side of the figure.

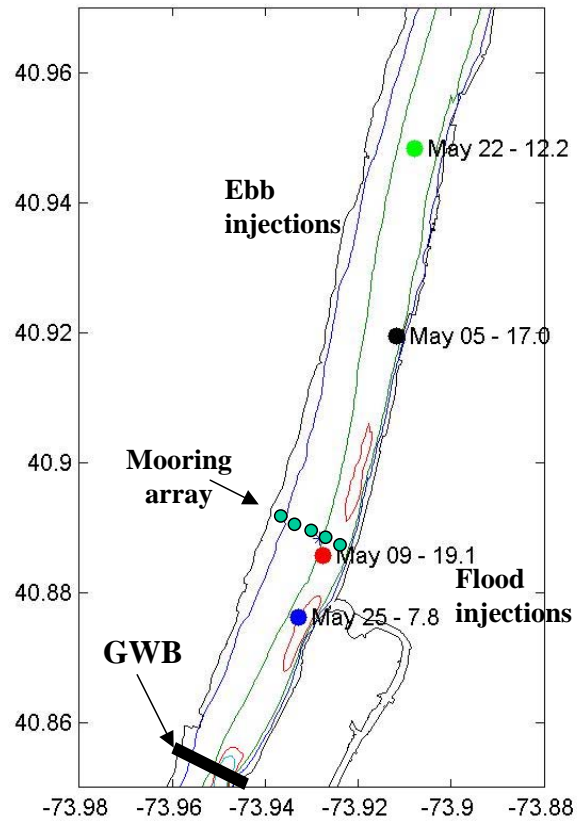


Figure 3. Location of mooring array and dye injections. The date and mean salinity at the injection depth are shown.

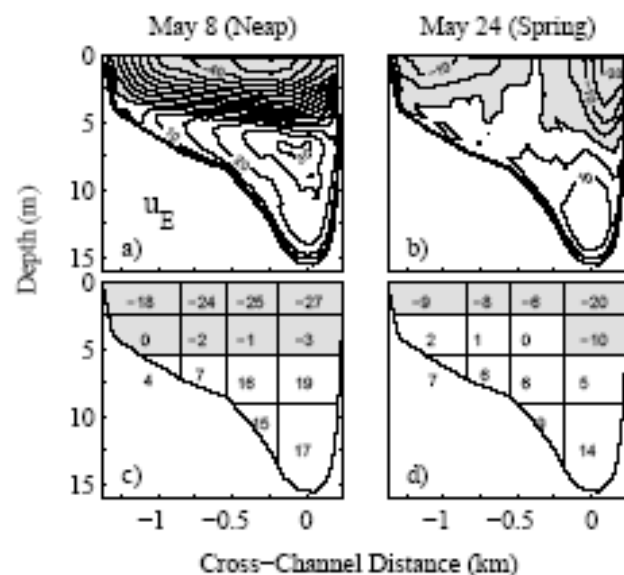


Figure 4: Cross-channel profiles of the estuarine circulation, u_e , during neap (left panels) and spring (right panels) tidal conditions. The upper panels were calculated from the cross-channel, tidal-cycle shipboard surveys. The contour interval is 5 cm s^{-1} , with 0 cm s^{-1} contoured with a thick line. The lower panels were calculated from the cross-channel mooring array over the same time period as the shipboard surveys. The values of u_e (in cm s^{-1}) are indicated for each sub-region. For all panels, oceanward (negative) currents are shaded gray.

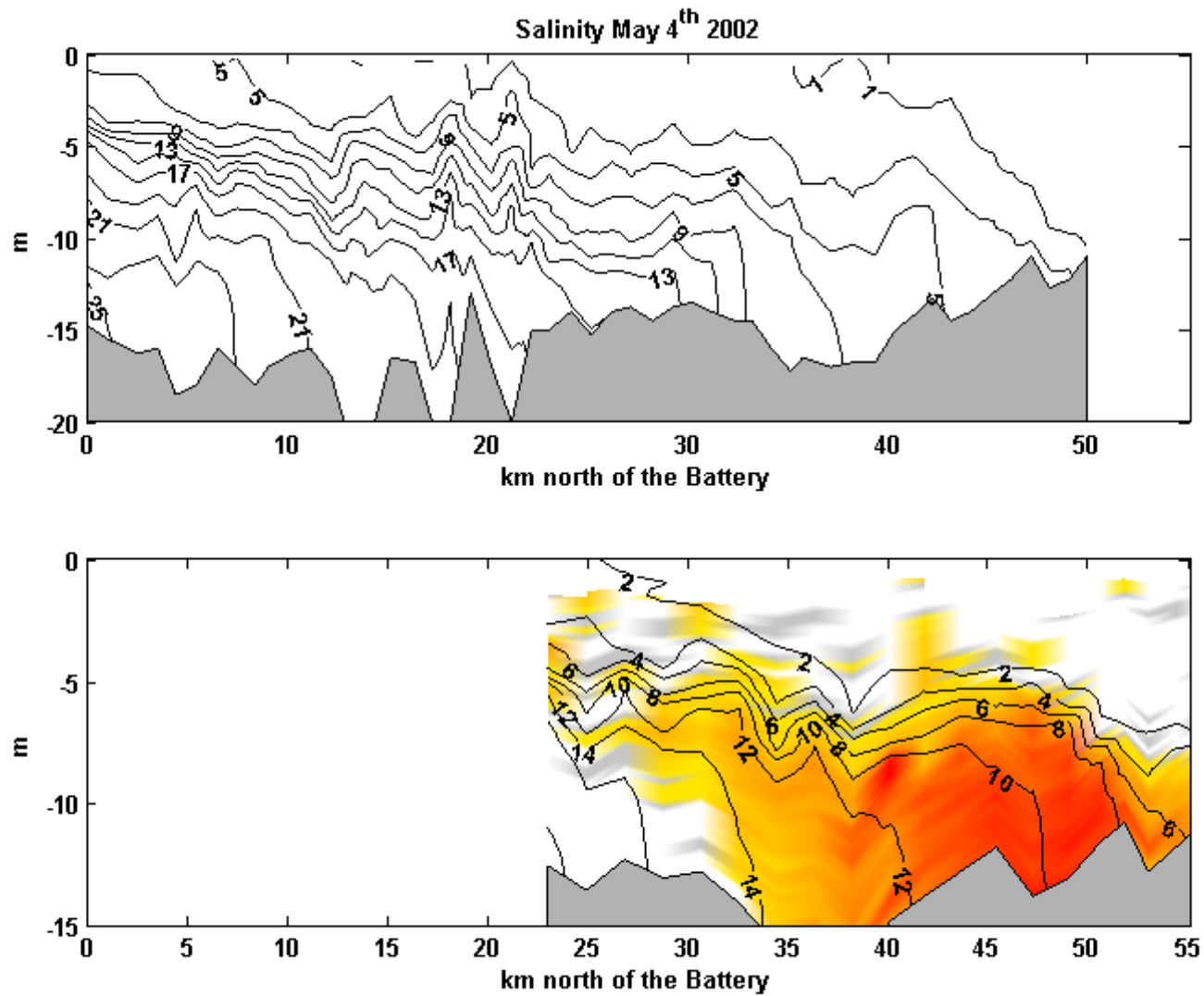


Figure 5 Salinity section on May 4th (one day prior to injection) And May 8th with dye (color) 3 days after injection.

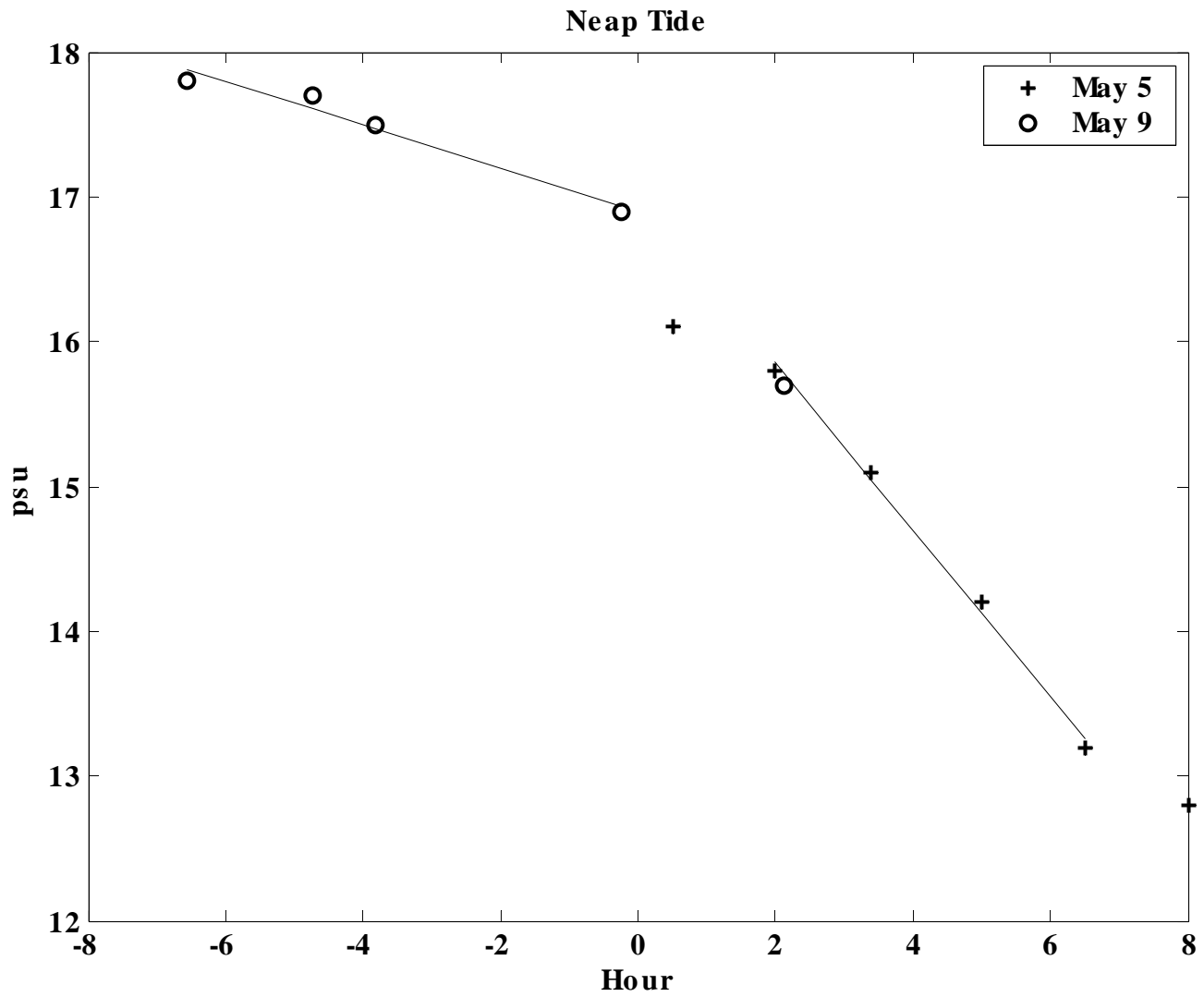


Figure 6 Patch mean salinity during neap tide experiments.

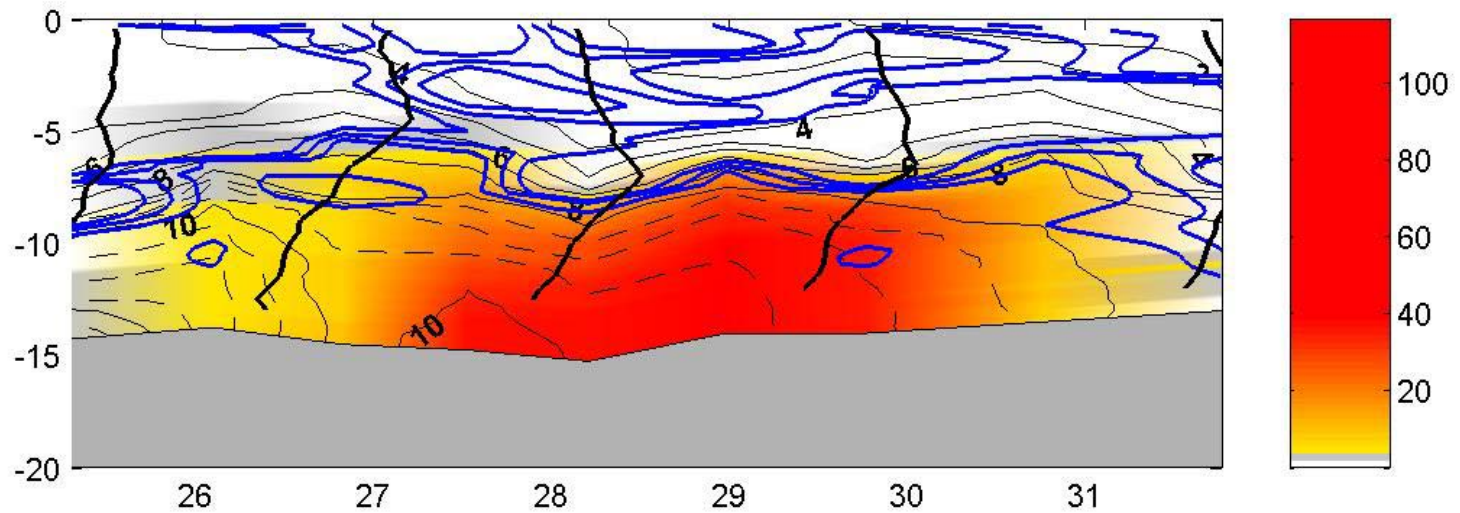


Figure 7. Flood tide May 22nd 2002. Dye concentration (color), salinity (thin solid and dashed lines), velocity profile (thick lines) and Richardson number (Blue Contours). The contour interval for the salinity contours is 1 out of the bottom boundary layer (solid lines) and 0.25 psu in the bottom Boundary layer (dashed lines). Richardson numbers are contoured at 0.25, .5 and 1 and the first contour line off the bottom is Ri=0.25.

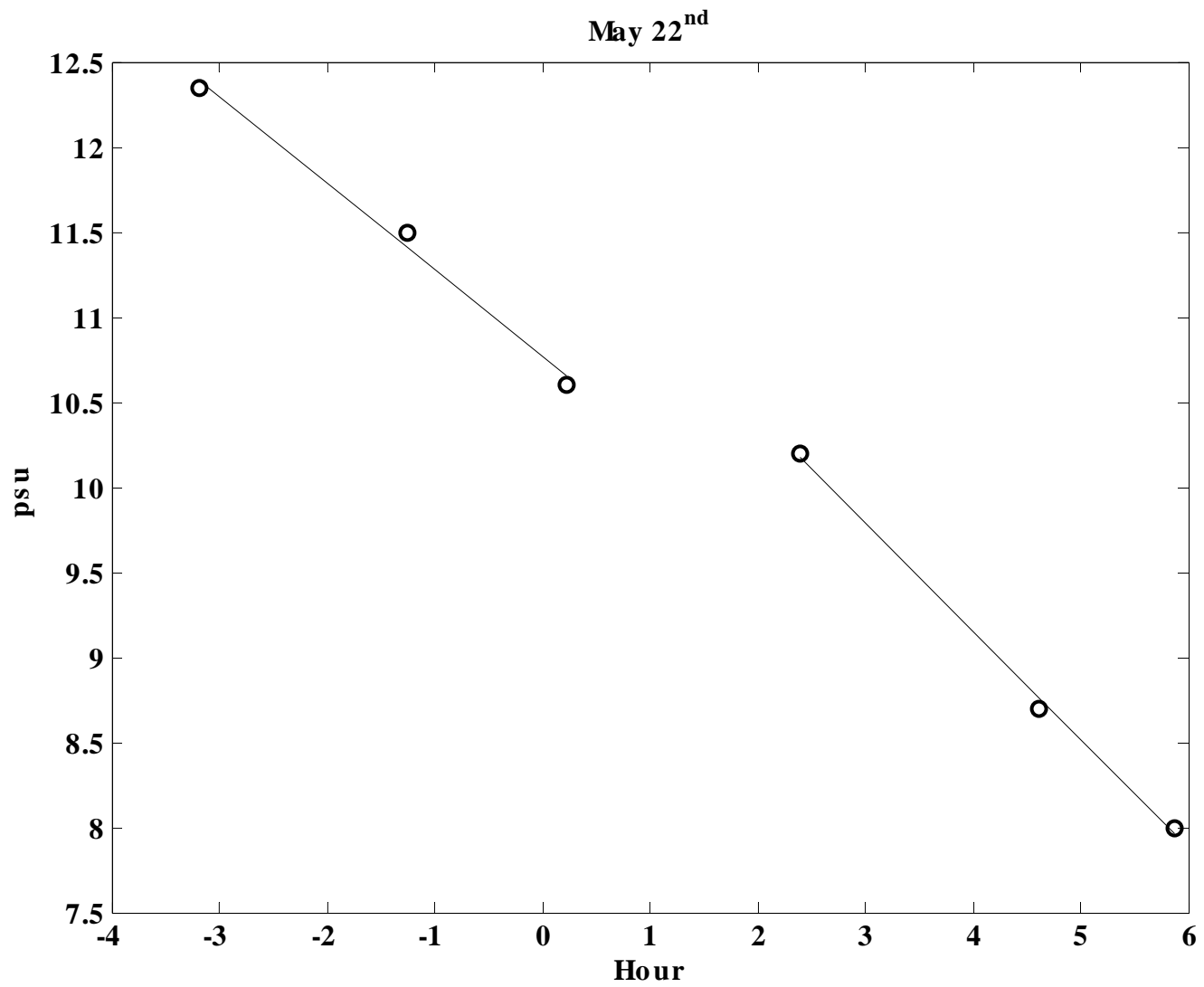


Figure 8. Patch mean salinity during transitional experiment.

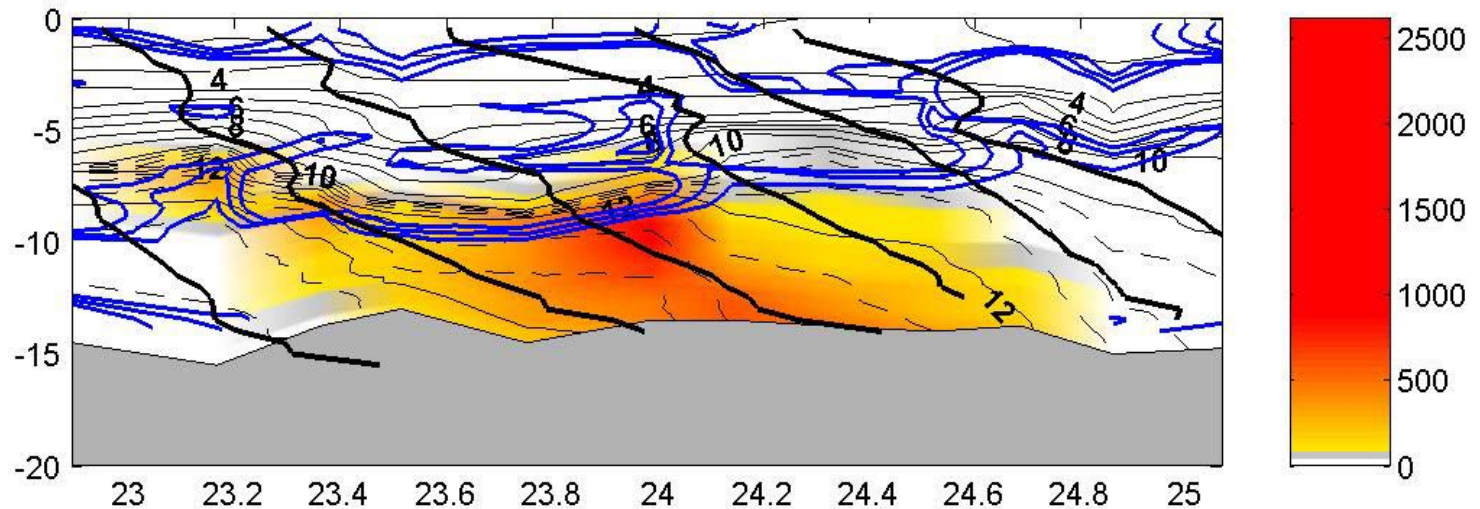


Figure 9. Ebb tide May 22nd. Dye concentration (color), salinity (thin solid and dashed lines), velocity profile (thick lines) and Richardson number (Blue Contours). The contour interval for the salinity contours is 1 out of the bottom boundary layer (solid lines) and 0.25 psu in the bottom Boundary layer (dashed lines). Richardson numbers are contoured at 0.25, .5 and 1 and the first contour line off the bottom is $Ri=0.25$.