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Indirect determination of the heat budget of tidal flats

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Abstract

A method is presented to calculate indirectly the heat budget of a tidal flat area from downstream observations of temperature and horizontal velocity in a tidal channel. It is only necessary to establish a relationship between the velocity and the volume flux. Then the heat budget of the upstream region is determined by integrating the heat flux over one tide. The proposed method is applied to long-term measurements obtained in 2004 at two sites in a tidal channel in the Hörnum Basin, German Wadden Sea. At the site located farther downstream in the channel, the upstream catchment area is diagnosed to export heat (heat gain in the interior) from March through August, while import is diagnosed for the same period of time at the other upstream site. From September through November the situation is reversed. An analytical estimate suggests that the sign of the budget is controlled by the tidal prism and the length of the dry-falling period of the flats in the respective upstream region. In addition, a simple model is developed which can be used to determine the integral bottom heat flux of the tidal flats.

Keywords: Germany; German Bight; Wadden Sea; tidal flat; heat budget; bottom heat flux

1 Introduction

In the present paper, a method is described to obtain a reliable estimate of the heat budget of tidal flats. The basic idea is to monitor the advective heat flux in tidal channels and then to calculate the heat excess or deficit for the catchment area by integral methods.

Tidal flats in Europe (except for the Mediterranean Sea) are flooded and drained twice a day by semi-diurnal tides. Hence, the boundary conditions are changing permanently with respect to biological, chemical and physical processes. Concerning physics, the rhythm of flood and ebb affects primarily the properties of the air-sea interface, and in conjunction with that the exchange of heat between the atmosphere and the underlying coastal seas.

The heat budget of a water volume fixed in space is simply the sum of the heat input through its boundaries and the production of thermal energy q_i inside the volume

Figure 1: Heat flux components in the ocean for a fixed water volume

(Fig. 1). At the upper horizontal boundary, i.e. the air-sea interface, the heat exchange is controlled by gain of the sun's shortwave irradiance q_{sw} , and by gains and losses due to infrared longwave radiation q_{lw} , latent heat exchange q_{lh} , and sensible heat transfer q_{sh} (for the meaning of the symbols see the Glossary section). Using q_b for the heat input through the bottom and q_a for the advective flux by currents through the lateral boundaries, the heat budget q reads

$$q = q_{sw} + q_{lw} + q_{lh} + q_{sh} + q_b + q_a \quad (1)$$

Here, the source term q_i (contributions are due to production of heat by biological activity, radioactive decay and molecular friction) has already been neglected because it is generally several orders of magnitudes smaller than all the other terms. By contrast, although considered to be negligible as well in oceanographic text books (e.g. Dietrich et al. 1980), q_b is important over tidal flats. This is because during low tide the temperature of the upper 10-cm mud layer may change by more than 10 K, and the corresponding heat is then released to the water layer during the ensuing flood (Andrews 1980).

Figure 2: Heat flux components over a tidal flat at low tide, flood, high tide, and ebb. The bottom is indicated by dark gray shading, water is light gray and air is white.

The authors are only aware of a few attempts in the past to determine the different components of the heat budget equation (1). Both for dry and wet tidal flats and different seasons, Andrews (1976) evaluated q_{sw} and q_b from direct measurements of the albedo and the bottom heat flux, respectively, and estimated the remaining vertical fluxes from Bulk formulae. One of his major conclusions was that the vertical fluxes of dry tidal flats are about 50% smaller than in case where the flats are covered by water. Unfortunately, he did not provide information on the total heat budget q . Vugts and Zimmerman (1985) parameterised the atmospheric fluxes and the bottom flux from direct measurements of meteorological parameters and bottom temperatures, and they were able to predict mean daily and hourly temperatures on a tidal flat in the Dutch Wadden Sea. Utilising a numerical model driven by observed atmospheric fluxes, Claussen (1988) evaluated the surface energy budgets of tidal flats. He was able to show that during low tide at daylight hours the flats store heat and release it to the water during the ensuing flood;

Figure 3: (a) Satellite image of the Hörnum tidal basin at low tide (Landsat Thematic Mapper, May 6, 2000). The positions of the measuring pile and the bottom mounted ADCP (bADCP) are indicated by yellow circles. Red lines indicate the tracks of the ADCP calibration surveys conducted in spring 2004. The area of the image is shown by gray shading in the map of the German Bight (b). Gray shading in (c) indicates the region of (b).

his results also indicate that during low tide at night the temperature of the flats decreases and cools the water as it becomes inundated.

The common ground of the above publications is that the heat budget has been determined from direct measurements of bottom and water properties and meteorological parameters. The method is promising, but only for a limited period of time and for a limited area, because observations are rather expensive. Therefore, a different approach is presented in this paper, which is simpler, more robust and less expensive: the heat budget of a tidal flat area is determined indirectly from observations of the advective heat flux through a tidal channel, comprising solely measurements of temperature and velocity.

The basic idea is sketched in Fig. 2, depicting the situation of the heat budget of a tidal flat and a channel during low tide, flood, high tide and ebb: at low tide, the bottom and the atmosphere exchange heat in terms of the vertical heat flux $q_{at} = q_{sw} + q_{lw} + q_{lh} + q_{sh}$, leading to a change of the bottom heat content; the advective flux in the channel

is zero, because there are no currents (slack water). During flood, there is a positive flux of heat towards the tidal flat by means of the advective flux q_a (onshore flow). At the same time, the heat content of the water column is modified by means of the ongoing atmospheric flux q_{at} , and in addition by the heat exchange q_b between the bottom and the water. The high water situation is characterised by zero advection of heat (slack water again), but the water temperature is subject to further changes by means of q_{at} and q_b . Finally, during ebb the water is drained off the flats, q_a being negative because the flow direction is offshore. Hence, the heat gain (or loss) Q_{tide} of the water over one tidal cycle from low tide to low tide can be determined by measuring

$$Q_{tide} = \int_{t_{low}}^{t_{low}^+} q_a dt = \int_{t_{low}}^{t_{low}^+} (q_{at} + q_b) dt, \quad (2)$$

where t_{low} indicates the time of the low tide, t_{low}^+ the time of the subsequent one, and t is time.

What remains is to measure the advective heat flux

$$q_a = QF_V = \rho c_p T F_V \quad (3)$$

for an arbitrary cross section of the tidal channel. Here, ρ is the density of the water, $Q = \rho c_p T$ the heat content and F_V is the volume flux through the cross section. For the calculations below, a constant value of $c_p = 4013 \text{ J kg}^{-1} \text{ K}^{-1}$ was used for the specific heat of seawater (Gill 1982).

Within the framework of coastal observation programs, the GKSS Institute for Coastal Research has conducted for many years long-term measurements of multiple oceanographic and meteorological parameters at different locations in the German Wadden Sea. As the majority of the stations is positioned in tidal channels and temperature and water velocity are constituents of the standard set of parameters acquired at every station, it is an easy task to determine Q_{tide} . The above method is tested utilising time series from the Hörnum tidal basin.

In the following, an overview is given of the region under consideration, and the GKSS observations system is presented. Thereafter, the new indirect method is applied to time series followed by a discussion of the results and the conclusions.

2 Geographic and oceanographic setting

The German North Sea coast is part of the Wadden Sea which fringes the Danish, German and Dutch coastlines between the peninsula of Skållingen in Denmark and Den Helder in the Netherlands over a distance of about 450 km (Fig. 3b, after Hofstede 1999). The Hörnum tidal basin is located in the German sector of the Wadden Sea. It is bounded in the east by the German mainland, in the south by the island of Föhr, in the west by the island of Sylt and in the north again by Sylt and the Hindenburg Dam (Fig. 3a). To the North Sea, the basin is connected by three inlets, the Hörnum Deep between Sylt and Amrum, the Föhr Shoulder between Föhr and the mainland, and

a nameless gap between Amrum and Föhr. While the Hörnum Deep reaches depths of more than 30 m close to the southern tip of Sylt, the Föhr Shoulder and the other gap are extremely shallow and only wet during high tide.

Based on two surveys in spring and fall 1996, Ross et al. (1998) calculated the residual volume fluxes through these inlets. For the Hörnum Deep, they found fluxes of -31 to $-115 \times 10^6 \text{ m}^3$ (negative sign means that the flux is directed out of the basin) depending largely on the weather situation and on the daily and fortnightly inequality of the tides. The corresponding numbers for the other gaps are 21 to $35 \times 10^6 \text{ m}^3$ for the Föhr Shoulder and 15 to $23 \times 10^6 \text{ m}^3$ for the gap between Amrum and Föhr. Hence, although the scatter of the numbers is quite large, the basin appears to gain a considerable amount of water through the shallow gaps, while there is a net export of volume by means of the Hörnum Deep.

As can be seen from Fig. 3a, the Hörnum Deep splits up into several branches. Observation stations are positioned at two bifurcations: a bottom mounted Acoustic Doppler Current Profiler (bADCP) at a water depths of about 8 m (Mean Low Water Springs) at the second major bifurcation, and a measuring pile at the third one at a depth of about 2 m.

3 The GKSS observation systems in the Hörnum tidal basin

Figure 4: The GKSS measuring pile in the Hörnum tidal basin.

For about the last decade, GKSS has acquired various oceanographic, meteorological and sometimes biologic parameters in very shallow water regions of the German sectors in the Baltic and in the North Sea. In the Hörnum Basin, the instrument assemblies relevant for this study are a measuring pile and a bADCP. Both are in operation during the ice-free season from about March to November since 2002.

The overall length of the measuring pile (Fig. 4) is approximately 18 m. The body consists of a 15-m long steel tube, 5 m of which are jettied into the sea bottom. A platform accessible via a ladder is mounted on top of the tube. The platform acts as a carrier for meteorological sensors (vane, anemometer, radiometer), solar panels for energy supply, logger boxes for temporary data storage and wireless communication, a flash light for security of ship traffic, and a winch. The purpose of the latter is to raise and lower the underwater unit for maintenance along the mechanical guidance. Finally, a tide and wave gauge are mounted laterally to the body.

The underwater unit is mounted so that the lower end of the sensor package is positioned approximately 1 m above the sea bottom. It is equipped with standard oceanographic instruments for recording pressure, temperature, conductivity and water velocity. Velocity is measured by two instruments: a Nortek ADV (Acoustic Doppler Velocimeter) records the velocity components at a fixed location below the instrument, while the ADCP is oriented horizontally (pADCP), measuring the lateral structure of the velocity field over a distance of 71 m, resolved into 14 bins of 5-m width each; the first bin starts at 1 m. The underwater unit also contains optical sensors for recording transmittance and turbidity.

The data from all instruments is sampled at high frequency, but because of the limited bandwidth of the wireless communication the data is first averaged over ten minutes and the averages are sent to the nearby land station. However, a rapid two-Hertz sampling mode may be enabled for a short period of time to record special events.

As the quality of the collected data is permanently subject to sensor fouling, e.g. by seaweed, mussels, barnacles and other organic material, the measuring pile is maintained at least once a week, even more frequently in summer when the water is warm. The major task of the maintenance personnel is to clean all instruments and sensors, and to monitor the calibration of temperature, conductivity, and optical sensors. An undesired side-effect of this mandatory procedure is that the underwater unit has to be hoisted out of the water, hence the data recorded during the maintenance period (approximately one hour) has to be removed later on.

The bADCP is an upward-looking self-recording device sitting right at the bottom of a tidal channel at about 10-m water depth acquiring velocity at 0.25 m vertical resolution (64 bins). Data is recorded at one-minute intervals and then averaged over 30 minutes to save storage space.

Figure 5: Volume fluxes in the Hörnum Deep observed by ship mounted ADCP at the locations of (a) the bottom mounted ADCP on 31 March and 1 April and (b) at the measuring pile on 29 and 30 March 2004. See Fig. 3a for the location of the ADCP transects.

4 The heat budget estimate of the Hörnum Basin, 2004

4.1 Volume flux calibration

The objective of this investigation is to develop a method to determine the heat budget of a tidal basin or a subregion simply from time series of velocity and temperature at a specific location in a tidal channel. According to (3) this requires knowledge of the temperature, the density and the volume flux in the channel. Assuming well-mixed conditions which are met at all times around the year, temperature and density can be calculated directly from the time series. Somewhat more delicate is the determination of the volume flux from single point measurements. To accomplish that a survey with a vessel mounted ADCP (vADCP) onboard RV “Ludwig Prandtl” was conducted in spring 2004 in the vicinity of the bADCP and the measuring pile, continually crossing the Hörnum Deep back and forth from one bank to the other, and recording the surface to bottom volume flux for each crossing. As it was regulated by law that the working time of the crew must not exceed ten hours, it was not possible to do continuous measurements over one full tidal cycle of about 12.5 hours. Therefore, the measurements at each of the monitoring stations were split over two successive days with sufficient overlap. The time series of the observed volume flux are shown in Fig. 5. At the location of the bADCP the flux varies between $-8861 \text{ m}^3 \text{ s}^{-1}$ at maximum ebb flow and $10717 \text{ m}^3 \text{ s}^{-1}$ (maximum flood), while the corresponding numbers for the pADCP are $-7640 \text{ m}^3 \text{ s}^{-1}$ and $8696 \text{ m}^3 \text{ s}^{-1}$, respectively; hence the extreme values at the bADCP are larger than at the measuring pile. Although it was not verified that these differences might be due to the daily inequality of the tides, they are reasonable because between the bADCP and the pile there are additional bifurcations of the Hörnum Deep which are fed by the flow observed at the bADCP location.

In order to establish a relationship between the observed volume fluxes and suitable proxy parameters at the mea-

Figure 6: Linear regression of volume fluxes observed by ship mounted ADCP with (a) the east component at intermediate depth recorded by the bottom mounted ADCP, and (b) the east component recorded by the pile-mounted ADCP. a_0 and a_1 are the regression coefficients, the correlation coefficient is given by C .

suring pile and the bADCP, respectively, a linear regression was performed for the fluxes shown in Fig. 5 and the velocity measurements performed by the bADCP and the pADCP. Fig. 6 displays the regressions for the east components of the bADCP and the pADCP, respectively. While the pADCP data were acquired about 1 m above the seabed in bin no. 1 about 3.5 m to the side of the underwater unit, those of the bADCP originate from about 5 m above the ground (bin no. 15). The correlation coefficients indicate an almost perfect regression for both devices, but the result for the pADCP is degraded by a clear hysteresis both for positive and negative velocity values. That means that for either identical pair of velocity values before and after maximum flood or maximum ebb, respectively, the corresponding volume fluxes are different. Apparently, this is due to the position of the pile at the bifurcation of the channel: during flood, one of the two branches is filled earlier (probably the southern one) and the volume flux diminishes more rapidly than in the other branch. The opposite happens during ebb. Such effect is not visible at the sections at the bADCP position.

4.2 Volume and heat flux at the bottom mounted ADCP

In 2004, the bADCP was in operation from March 23 through September 27. A time series of the volume flux $F_V(t)$ was calculated from the velocity east component of bin no. 15 and the previously derived calibration coeffi-

cients (Fig. 7a; the scaling of the time axis is identical to Fig. 9). The series exhibits the common signatures of a semi-diurnal tide, daily and fortnightly inequalities. The long-term behaviour of the volume flux is visualised by graph b below, displaying the cumulative (net) volume exchange

$$V_{cum}(t) = \int_{t_0}^t F_V(t) dt \quad (4)$$

where t_0 is the starting time. The negative trend of V_{cum} indicates a permanent “downstream” net volume flux in the Hörnum Deep at this location, i.e. directed to the North Sea. In total, this amounts to a net loss of 9 km^3 over the entire integration period of about 185 days, which is equivalent to $2.5 \times 10^7 \text{ m}^3$ per tide. Apparently, this is due to the residual flow around the island of Föhr entering the basin via the Föhr Shoulder and leaving it via the Hörnum Deep. The latter number is in good agreement with the findings of Ross et al. (1998), who obtained from direct measurements $2.1 - 3.5 \times 10^7 \text{ m}^3$ for the same quantity.

In order to calculate the corresponding heat flux correctly, the ebb flow of each individual tide was weakened artificially in a way that the net ebb volume flux balanced exactly the net flood volume flux of the previous semi-tide. This was done by linear scaling of the instantaneous ebb velocity with the normalised tidal residual volume flux, balancing the net flow around Föhr. In this way, the contribution of the volume flux between Föhr and the mainland is definitely removed, but there remains a potential error due to the different temperature characteristics of that water compared to the water masses in the catchment area. It is assumed that this error is small on average. The result of this procedure is the balanced instantaneous heat flux q_a shown in Fig. 7c. In addition to the volume flux in the uppermost panel, one can clearly see the seasonal warming trend until early August and the successive cooling in autumn. As this graph does not exhibit any details about the heat budget of the upstream basin, the instantaneous heat flux timeseries was split into 362 individual tidal cycles, and then the heat budget Q_{tide} was calculated for each tide. The result (Fig. 7d) exhibits an oscillating pattern with half the frequency of q_a , i.e. the integration over each semi-diurnal tide creates a diurnal signal. It is conjectured at this instant that the tidal heat budget depends on the day/night cycle of the air-sea heat flux. Details will be shown below. To arrive at a clearer picture, the cumulative heat budget

$$Q_{cum}(t) = \sum_{t_0}^t Q_{tide}(t) \quad (5)$$

is shown in Fig. 7e. Now, it becomes evident that the upstream basin is exporting heat from March through early August by advection, and importing heat later on. The early August value of Q_{cum} is $\approx 20 \text{ PJ}$, hence the average export rate over the preceeding 140-days period is $\approx 1.7 \text{ GW}$.

The export rate above is contributed by the air-sea and bottom heat flux integrated over the catchment area of the water passing along the bADCP. In order to provide a rough estimate of the size of that area, the TRIM (Tidal,

Figure 7: 2004 time series at the bottom mounted ADCP: instantaneous volume flux (a), cumulative volume exchange (b), instantaneous balanced (see text) heat flux (c), net heat exchange over one tide (d), cumulative net heat over one tide (e) mean net heat over one tide averaged over one tropical month (f), temperature difference between mean flood and mean ebb temperature (g).

Residual, and Intertidal Mudflat Model) primitive equations model was utilised for the Hörnum Basin. TRIM is used in a version which is described in more detail in Casulli and Cattani (1994) and Casulli and Stelling (1998). It simulates currents, water level, and flooding and drying of tidal mud-flats, but thermodynamic fluxes are not included. The model is nested four-fold (800m, 400m, 200m, 100m) within the operational model of the *Bundesanstalt für Seeschifffahrt und Hydrography, BSH* (Dick et al. 2001), the horizontal resolution of the BSH model is 1 nautical mile.

Based on the TRIM output and for a situation representing approximately mean conditions in November 1999, the trajectories of Lagrangian water particles were computed: 1000 particles were marked at six discrete instants during flood and positioned within the white triangle indicated in Fig. 3. Their final position at the subsequent high tide is shown in Fig. 8. Determining a catchment area of 55 km² from that figure, the mean combined air-

sea and bottom heat flux density amounts to about 31 Wm⁻² (gain) in the interior of the basin. In order to provide an error estimate of the latter number which is proportional to the size of the catchment area, TRIM was re-run for spring and neap tide conditions and for storm events. As a result, the catchment area size changes by about $\pm 30\%$.

In another representation (Fig. 7f), Q_{tide} was averaged over one tropical month (≈ 27 days). The resulting Q_{mean} is negative from March through middle of August, changing sign thereafter. The sign of this number was validated by evaluation of the difference ΔT between the mean flood and ebb temperatures and again averaging this differences over one tropical month (Fig. 7g). This graph is almost identical to the above one: from March through middle of August ΔT is negative, which means that the water returning from the tidal flats (ebb flow) is warmer than the water during the previous flood.

Figure 8: The catchment areas of (a) the bottom mounted ADCP and (b) the measuring pile were determined by a numerical model and are indicated by the cross hatched area. For the determination, 1000 Lagrangian particles were released within the white polygons in one-hour intervals during flood, and their final positions at the subsequent high tide was calculated. Tidal flats are indicated light-gray.

4.3 Volume and heat flux at the measuring pile

The same procedure as described in the above subsection was applied to the pADCP, the results being displayed in Fig. 9. Contrary to the bADCP, the pADCP was in operation from March 9 to November 9, 2004 with some major interruptions in May/June and September/October because of instrument malfunction, clearly visible in panel a. Hence, the real operational period was 211 days. As at the bADCP, the cumulative volume exchange V_{cum} (panel b) is negative, the net loss being 6.3 km^3 over 211 days or $1.5 \times 10^7 \text{ m}^3$ per tide. This number is 60% of the corresponding value at the bADCP, a reasonable value because part of the flow surrounding the island of Föhr appears to take a course south of the pile close to the island. The instantaneous balanced heat flux q_a (panel c) resembles closely that at the bADCP, but the graph of the heat budget is significantly different (panel d). In particular, there is also a diurnal cycle, but the amplitude at the pADCP is larger and Q_{tide} is more positive. The latter is confirmed by Q_{cum} (panel e) which increases from March through August – contrary to the situation at the bADCP where an export of heat was diagnosed, the basin upstream of

the pile is importing heat for most of the time. Later on, the heat budget is almost balanced and from mid October the budget changes to export. For the total import March through August of about 10 PJ and a catchment area of 34 km^2 (cf. Fig. 8) the average import rate is of the order of 0.83 GW , corresponding to a heat loss of $24 \pm 10 \text{ W m}^{-2}$. In agreement with panel e, Q_{mean} (panel f) is positive from March to the end of August, close to zero in September and then becomes negative in October. The contrary behaviour of the upstream basin is also validated by panel f, indicating that the mean flood temperature is higher than the mean ebb temperature from March through August.

4.4 Differences of thermodynamical characteristics

The inverse behaviour of the heat budget of the basin upstream of the bADCP and the pile, respectively, can only be due to the different geographical positioning of the monitoring systems. The following investigations are based on the working hypothesis that the heat budget characteristics at the pile is mainly controlled by the thermodynamic properties of dry-falling tidal flats, while that at the bADCP, located farther downstream, exhibits to a larger degree the properties of the thermodynamics of tidal channels. The hypothesis is based on the fact that the fraction of the water volume exchanged within one tidal cycle and the total volume within the catchment area (i.e. the tidal prism) is much smaller for the bADCP than for the pile: at high water, the mean depth of the catchment area of the ADCP is about 6 m (estimate from sea chart), which yields a total volume of $3.3 \times 10^8 \text{ m}^3$, $1.75 \times 10^8 \text{ m}^3$ or 53% of that exchanged within a tidal cycle (see above). By contrast, the mean depth of the catchment area of the pile is definitely lower. Even if one assumes an upper bound of 5 m, the total volume there is only $1.7 \times 10^8 \text{ m}^3$; 87% ($1.48 \times 10^8 \text{ m}^3$) is exchanged by the tide. Hence, the major part of the catchment area of the pile is flushed twice a day, which is not the case for the bADCP. Furthermore, because there is strong evidence for a diurnal cycle of Q_{tide} , the previous calculations of Q_{tide} have been repeated both for the bADCP and the pile, but now taking into account the relationship between the tide and the time of the day.

First of all, the time coordinate of the time series was converted from UTC (Universal Time Coordonné) to the local time at the positions of the monitoring systems. As the longitude of the latter is $8^\circ 25' \text{ E}$, the local time is UTC + 34 minutes. Q_{tide} at the bADCP is shown in Fig. 10, both as a contour plot displaying Q_{tide} as a function of the time of the year and the high water time t_{high} , and as a function of t_{high} , only (note that a tide is defined between two successive low waters, t_{high} being approximately centred). According to the contour plot, Q_{tide} is nearly always negative in March and April, and from May through early September when t_{high} is around noon. In those cases, the upstream region is exporting heat. In contrast, it is positive in late September and from about May through early September when t_{high} is centred around midnight. This is equivalent to heat import. However, one must not overinterpret this plot, because at any day of the year the

Figure 9: Same as Fig. 7 but at the measuring pile.

contours are based on two t_{high} values at best. More information can be gained from the right panel of Fig. 10, which was rotated by 90° in order to be consistent with the left panel: here, the Q_{tide} values of each individual tide (362 in total, see above) are indicated by dots at the respective t_{high} value, and the solid line is the mean. Although there is a wide scatter of the dots, one can clearly see from the mean that the upstream region is exporting heat when t_{high} is during daylight hours (note that the gray shading indicates night at the equinoxes, only), and importing heat otherwise. The maximum heat export of close to 450 TJ occurs when t_{high} is at noon; this is apparently in early June (left panel). Extreme import values of up to 300 TJ occur when the tidal cycle is at night; there is some indication of a double maximum at 3h and 21 h. Based on these extreme values one arrives at a heat gain of 182 Wm^{-2} or a loss of 121 Wm^{-2} , assuming again an upstream catchment area of 55 km^2 .

At the pile, the situation is different. Here, the upstream region also exports heat (red contour fills in Fig. 11) when t_{high} is during daylight hours, but the temporal window of the export situation is smaller than at the

bADCP, i.e. almost at any time of the year the export switches to import (blue) when t_{high} is between about 21h and 3h. Only in late September, October, and early November is there some indication of an export situation for t_{high} at night. Overall, import appears to be more frequent and intense compared to the bADCP. The latter is also reflected by the right panel of Fig. 11, indicating import ($Q_{tide} > 0$) even when t_{high} is during daylight hours in the morning or in the evening. Moreover, the maximum import values at night, reaching about 450 TJ, are greater than at the bADCP, and correspond to a heat loss of about 294 Wm^{-2} . In turn, the maximum export value is close to 500 TJ yielding a heat gain of 326 Wm^{-2} .

5 Discussion

5.1 Applicability of methods

The above results have shown the feasibility of determining the heat budget of the water in tidal-controlled regions. It is solely necessary to measure continuously the water temperature and the volume flux at choke points, i.e. in

Figure 10: 2004 net heat exchange over individual tides, Q_{tide} (in TJ), at the bottom mounted ADCP. Left panel: Contour plot of Q_{tide} in dependency of the daynumber and high tide time t_{high} . Right panel: Q_{tide} as a function of t_{high} (dots); the solid line is the average of Q_{tide} for any t_{high} . Gray-shading indicates night, approximately. t_{high} is in local time, rounded to the full hour.

tidal channels which have to be passed through by the water exchanged during each tide. The minimum requirement is to conduct the measurements over one full tidal cycle from low tide to low tide, and then to determine the change of the heat content by integrating the heat flux. If the integral is negative, then the upstream region is exporting heat (heat gain), a positive sign indicates heat loss. Moreover, if the catchment area of the upstream region is known, it is straightforward to calculate the combined thermal output of the air-sea energy exchange and the exchange between the water column and the seabed. If one is only interested in qualitative results, the measurements become even less expensive, because it is only necessary to determine to sign of the difference between the mean ebb and flood temperatures. This method, however, may lead to wrong results, because the mass weighting is neglected (cf. (3)).

5.2 Explanation of physical processes

In the present work, the heat budget was evaluated at two different choke points – the bADCP and measuring pile – the latter lying about 4.6 km upstream of the bADCP in the same tidal channel. For both points, an average thermal output between 24 and 31 Wm^{-2} was diagnosed for the period March through August, being negative at the bADCP and positive at the pile. This disagreement is due to systematic differences of the heat budget Q_{tide} of the respective upstream region for individual tides: at the bADCP, Q_{tide} is negative (export) when high tide is during daylight hours and positive at night, i.e. the width of the time window for export is about twelve hours with

respect to high tide time. The window for import is about the same width, but the Q_{tide} values are generally lower than the absolute Q_{tide} values in the export situation. Therefore on average, export of heat prevails. This situation is typical for open ocean conditions at moderate latitudes (cf. Dietrich et al. 1980), where the heating season lies approximately between the equinoxes. Hence, one can conclude that the thermodynamic properties of the catchment area upstream of the bADCP are comparable to open ocean conditions: the net air-sea heat exchange is mainly controlled by the shortwave and longwave radiation budget. Namely, the latent and sensible heat fluxes are also important, but their seasonal variability is much smaller. By contrast, at the pile the situation is different in that the width of the export window is only nine hours and that of the import window 15 hours. This, together with the larger Q_{tide} values corresponding to import, leads to import on average.

In order to explain these systematic differences, it is assumed that the air-sea fluxes would be identical at any point in the Hörnum Basin if there were no tidal flats. In that case, Q_{tide} would have the same sign at the pile and the bADCP. However, the sign is different and this can only be due to the existence of tidal flats. In order to provide a more detailed explanation, the thermodynamic history of a hypothetical Lagrangian water particle under different extreme conditions is sketched for a typical summer situation:

- Case 1a: t_{high} around noon, no contact with tidal flats: the particle enters the tidal basin with the flood in the morning and leaves the basin in the afternoon. As it never gets in contact with tidal flats, the heat

Figure 11: Same as Fig. 10 but at the measuring pile.

budget of the particle is only controlled by the air-sea heat flux in the tidal channel, being generally positive. The particle gains heat all the time during the tidal cycle and its ebb temperature in the afternoon is higher than the temperature during flood in the morning. This case is typical for the bADCP export case.

- Case 1b: t_{high} around midnight, no contact with tidal flats: the particle enters the basin with the flood in the evening and leaves the basin after midnight. As q_{sw} is close to zero during this period of time, the heat budget is negative, because q_{lw} , q_{lh} , q_{sh} are generally directed from the ocean to the atmosphere. The particle loses heat all the time during the tidal cycle and its ebb temperature at night is lower than the temperature during flood in the evening before. This case is typical for the bADCP import case.
- Case 2a: t_{high} around noon, contact with tidal flats: the particle enters the basin in the morning and flushes a tidal flat. As in Case 1a, the air-water heat flux is positive, but on the tidal flat the particle in addition loses heat due to the negative bottom heat flux q_b . This is negative, because during the preceding dry-falling period at night the tidal flats were cooling due to heat loss. During ebb in the afternoon, the air-water heat flux is still positive, but q_b is zero because the bottom and water temperatures are now in equilibrium. Overall, export prevails, but the integral heat export Q_{tide} is less than in Case 1a because of the negative contribution of q_b in the morning. Case 2a is typical for the export situation at the pile. Moreover, if t_{high} is shifted to sunrise then the entire flood period is during night and q_b even becomes more negative. As the air-water fluxes are also negative, the export

switches to import. However, by these arguments it is somewhat difficult to explain the change of sign of Q_{tide} at the pile when t_{high} is late in the afternoon. It is therefore conjectured that in cloudy conditions q_b is frequently negative, even when the flood is during daylight time. This is reasonable because q_{lw} , q_{lh} , q_{sh} , being negative, cannot be balanced by q_{sw} .

- Case 2b: t_{high} around midnight, contact with tidal flats: this case is similar to Case 1b, but now the particle loses additional heat during flood because of the relatively cold tidal flats and the corresponding negative bottom heat flux q_b . It is representative for the import situation at the pile.

Summarising, there is a consistent qualitative explanation of the different behaviour of Q_{tide} at the pile and the bADCP: it is the additional cooling of water during flood due to the mostly negative bottom heat flux when the water enters the tidal flats at night or in the early morning. Apparently, the cooling is more efficient for water particles passing the pile, and one might speculate why. A potential cause could be that the fraction of tidal flats relative to the catchment area is larger for the pile than for the bADCP. This was examined on the basis of Fig. 8, but surprisingly the fractions are almost identical – both for the pile and bADCP the fraction of the dry-falling areas is around 24%. Another possibility would be that the exposure time of the tidal flats to the atmosphere (i.e. the length of the dry-falling period) is different for each catchment area. As there is no data available for this quantity, the mean residence time of particles on the tidal flats must be estimated; for particles passing the bADCP, it can be expressed as

$$R_1 = \tau \frac{hA_1}{V_1}, \quad (6)$$

where V_1 is the volume exchanged within one tidal cycle at the bADCP, A_1 is the area of the tidal flats in the catchment area, h is the thickness of the water layer covering the tidal flats in the catchment area at high tide, and $\tau = 44700$ s is the length of the tidal cycle. Using $A_1 = 13.4 \text{ km}^2$ (evaluated from Fig. 8), $h = 2 \text{ m}$ and $V_1 = 1.75 \times 10^8 \text{ m}^3$ (taken as mean values from the measurements), one arrives at a mean residence time of close to two hours. For particles passing the pile, the corresponding residence time

$$R_2 = \tau \frac{hA_2}{V_2} \quad (7)$$

is only around 80 minutes ($A_2 = 8.2 \text{ km}^2$, $V_2 = 1.48 \times 10^8 \text{ m}^3$). Hence the exposure time of the tidal flats in the catchment area of the pile is significantly longer, which leads to a more efficient cooling of the flats at night. Note that (6) and (7) provide only a first guess of the residence times; in the case of $h = 0$ (no water on tidal flats at any time), $A_1 = 0$ or $A_2 = 0$ (no tidal flats at all), the residence times are zero which makes sense. By contrast for the other extreme cases $hA_1 = V_1$ or $hA_2 = V_2$ (total exchanged volumes on tidal flats), the residence times are equal to the tidal cycle.

All the above explanations hold only for spring and summer, and it is rather speculative what happens in autumn and winter. From Figs. 7 and 9, there is clear evidence that the situation reverses in August at the bADCP and in September/October at the pile. For the bADCP, it would be sufficient if the bottom flux were negligible compared to the air-sea fluxes, and the thermodynamic system would then behave like the open ocean, simply with heat loss in the upstream region (import). This situation would also prevail in winter. At the pile, however, the system switches to export which is quite difficult to explain. As the air-sea heatflux for the region upstream of the pile is definitely negative, one must conclude that the bottom heat flux is positive. This can only mean that the tidal flats are storing heat while being dry, and release the heat to the water column during the upcoming flood. This is also supported by the direct measurements of Andrews (1980), which provide clear evidence that in autumn, winter and early spring the bottom of tidal flats warms the overlying water.

5.3 The bottom heat flux on tidal flats

From the previous considerations it has emerged that the bottom heat flux on tidal flats controls the sign of the net heat flux at downstream choke points. In the following, a simple analytical model is presented to determine this flux from the experimental data. If one considers a Lagrangian water particle shaped as a cube with a volume of $V_0 = 1 \text{ m}^3$, passing the bADCP upstream during flood at time t_f and downstream during the successive ebb at time t_e , the heat content change ΔQ_1 of the particle experienced during its trip in the upstream region is

$$\Delta Q_1 = \int_{t_f}^{t_e} q_{at_1} dt + \int_{t_{arr_1}}^{t_{dep_1}} q_b dt + \Delta Q_{mix_1}. \quad (8)$$

Here, t_{arr_1} is the time when it arrives on a tidal flat, t_{dep_1} is the departure time, and ΔQ_{mix_1} is the heat exchange

by turbulent mixing with the “underlying” water which was already in the channel at low tide and never passes the bADCP. An equivalent equation

$$\Delta Q_2 = \int_{t_f}^{t_e} q_{at_2} dt + \int_{t_{arr_2}}^{t_{dep_2}} q_b dt + \Delta Q_{mix_2} \quad (9)$$

holds for the pile. Assuming q_b to be time-independent, the bottom flux integrals can be substituted by $q_b R_1$ and $q_b R_2$, respectively, where R_1 , R_2 are the residence times of the particle on the tidal flats (see above (6)). Under the assumption that the heat exchange with the atmosphere is the same for both particles, $q_{at_1} = q_{at_2}$, then by subtracting (8) from (9) one obtains for the bottom heat flux

$$q_b = \frac{(\Delta Q_2 - \Delta Q_{mix_2}) - (\Delta Q_1 - \Delta Q_{mix_1})}{R_2 - R_1}. \quad (10)$$

Furthermore, it is postulated that the individual heat content changes of the particles are a function of the total heat exchanges at the choke points, and P_1 , P_2 express the probability that the particles reach a tidal flat:

$$\Delta Q_1 = P_1 Q_{tide_1} \frac{V_0}{V_1}, \quad \Delta Q_2 = P_2 Q_{tide_2} \frac{V_0}{V_2} \quad (11)$$

(note that V_0 has to be carried along for dimensional correctness). The probabilities, in analogy to the residence times above, are

$$P_1 = \frac{hA_1}{V_1}, \quad P_2 = \frac{hA_2}{V_2}. \quad (12)$$

Finally, the turbulent heat exchanges may be expressed as

$$\Delta Q_{mix_1} = a \Delta Q_1 \quad (13)$$

and

$$\Delta Q_{mix_2} = b \Delta Q_2, \quad (14)$$

where the coefficients a, b are the ratios of the volumes exchanged during one tidal cycle and the total volumes of the basin at high tide, for both choke points. After substitution of (11) – (14), the equation for the bottom heat flux normalised by the unit volume reads

$$\frac{q_b}{V_0} = \frac{(1-b)A_2 V_1^2 Q_{tide_2} - (1-a)A_1 V_2^2 Q_{tide_1}}{\tau(A_2 V_1^2 V_2 - A_1 V_2^2 V_1)}. \quad (15)$$

In order to compare the heat flux with those from previous studies, the quantity

$$q'_b = A_0 \frac{q_b}{V_0} \quad (16)$$

is considered in the following, where A_0 is the unit surface. By this transformation, q'_b represents a flux density in physical units of Wm^{-2} . Fig. 12 shows that this formula yields reasonable values for q'_b using $a = 0.53, b = 0.87$ (see above section 4.4). As according to Figs. 10, 11 the difference between Q_{tide_1} and Q_{tide_2} never exceeds 400 TJ for a specific time of the day, the parameter range is masked out where $|Q_{tide_2} - Q_{tide_1}| > 400 \text{ TJ}$. Fig. 12 can be used as a handy tool to determine the mean bottom heat flux q'_b . For example, choosing $Q_{tide_1} = -200 \text{ TJ}$,

Figure 12: The modelled bottom heat flux q'_b [Wm^{-2}] as a function of the tidal net heat exchanges Q_{tide1} and Q_{tide2} at the bADCP and the measuring pile, respectively. Only those cases are considered, where $|Q_{tide2} - Q_{tide1}| \leq 400$ TJ, because larger differences are never observed according to Figs. 10, 11.

$Q_{tide2} = -150$ TJ, yields $q'_b \approx -35 \text{ Wm}^{-2}$, reflecting approximately the mean noon situation of Figs. 10 and 11.

In order to evaluate the long-term mean bottom heat flux on the tidal flats, (15) is applied to the time series of Q_{mean} shown in panels f of Figs. 7 and 9, and representing the running mean of Q_{tide1} and Q_{tide2} , respectively (Fig. 13): from April through about 20 August, q'_b is negative, i.e. the bottom is cooling the overlying water. Apparently, during low tide in summer at daylight time, the net heat gain of the bottom is not sufficient to compensate for the losses of the previous night. This is plausible, because the daytime heating of the flats by absorption of short-wave radiation affects only the upper about 10-cm layer (Andrews 1980), while in the wet case the incoming radiation is absorbed completely by the water column. In addition, the albedo of the flats is generally twice as large as that of water (Andrews 1976). Although no validation measurements were taken, the authors are convinced that also the magnitude of the numbers is right: under fair weather conditions in summer, the amplitude of the bottom temperature reaches about 10 K within one tidal cycle (Andrews 1980), which is equivalent to an “efficient” temperature amplitude of about 4 K within the upper 25 cm. The latter is the vertical e-folding scale of the diurnal temperature wave. If this heat is released within one tidal cycle, the average bottom heat flux amounts to about 90 Wm^{-2} . Andrews (1980) determined this number from direct measurements in the Ems/Dollart estuary, and for the daily mean bottom fluxes he arrived at -17 Wm^{-2} on a fair day in June. This value is very close to the corresponding values in Fig. 13, where in June values are between about -20 Wm^{-2} and -5 Wm^{-2} . Moreover, the sign change of q'_b in late August was observed by Andrews (1980) as well, and he confirms also another change of sign in March. This supports the conjecture that q'_b becomes positive in winter, although the physical mechanism is

not at all clear to the authors.

Figure 13: The bottom heat flux q'_b (solid line) on the tidal flats. The dashed and dot-dashed lines are the tidal net heat fluxes Q_{mean} at the bADCP and the pile shown in Figs. 7f and 9f, respectively.

5.4 Possible sources of error and representativity of the results

This study has shown that it is feasible to determine the heat budget of parts of the Hörnum Basin by indirect methods, and that the budget depends crucially on the position of the choke points. In the present case, even the sign is different at the selected choke points. This is an important finding and it is necessary to check by how far this result is sensitive to errors, which can just be measurement errors or intrinsic errors in the applied methods.

The only directly measured quantities are temperature and velocity, both at the bADCP and the pile, and the volume transports determined from vADCP. On the pile, temperature is acquired by a platinum thermometer, which is calibrated in the lab once a year in winter and additionally cross-checked almost every week within the framework of the routine maintenance. Moreover, there are additional temperature sensors on the pile in the pADCP and the ADV. Except for systematic offsets among the different sensors, no specific malfunction of the platinum thermometer was diagnosed. Concerning the offsets, these are not critical because the heat budget is evaluated only over individual tides (cf. (2)) which cancels out systematic errors. The same argument holds as well for the temperature sensor in the pADCP and for the velocity measurements at the bADCP and on the pile (pADCP). No information is available about errors of the volume transport calculations derived from vADCP velocity measurements, because they are included in the commercial VISEA[®] software utilised for the acquisition and processing of ADCP data.

Equation (2) (and the corresponding Fig. 2) is based on the assumption that the water bodies passing the choke point during flood and ebb are identical. This is truly the case when the upstream catchment area is falling dry during low tide. In reality, however, the water bodies are not identical, because the catchment area is crossed by tidal channels which are never dry, and the water remaining in the channels during low tide will mix with the incoming water during the next flood phase acting as an additional source term in (2). In addition, large parts of the lateral boundaries of the catchment are wet at all times and horizontal mixing between the incoming water and the ambient fluid will take place. In principle, also with the help

of a numerical model, it would be possible to estimate the magnitude of those heat sources, but this would require at least the knowledge of the second derivative of the horizontal and vertical temperature distribution. As not even the temperature distribution is known, such estimates are not feasible and one is left to assume that the heat sources due to mixing are negligible for budget calculations.

According to (3), the calculation of the advective heat flux requires knowledge of the density of seawater which is a function of temperature, salinity and pressure. As the pressure dependency can be neglected in the present case (shallow water and pressure constant in time), taking account of salinity changes would be desirable, because in the Hörnum Deep salinity variations of up to one practical salinity unit may occur within a tidal period. Salinity time series are available at the pile, but the basic conductivity measurements are frequently corrupted because of bio-fouling. Therefore, for the calculation of density the salinity was assumed constant at 30.5 which is a reasonable mean value for that region. To be safe, the above calculations were repeated for the pile with taking account of the available salinity observations, and fortunately there was no significant change of the heat flux calculations. This gives some confidence in the results also at the bADCP where no conductivity measurements are available.

In order to calculate the net heat flux over individual tides correctly it was mandatory to equilibrate the integral volume fluxes during flood and ebb, respectively; these were out of balance due to the net inflow into the Hörnum Basin over the Föhr Shoulder. This procedure is problematic, because it might induce errors in the heat budget analysis. For example, if the temperature of that inflow were generally different from the temperature of the ebb flow water in the Hörnum Basin, this would introduce a systematic bias in the calculations of Q_{tide} – in the worst case it could lead to a change of sign. However, as the inflow is felt both at the pile and the bADCP, the bias should be qualitatively similar at both positions. The authors are quite sure that no such bias exists because from similar analyses of a measuring pile positioned in the East Frisian Wadden Sea (Flöser, personal communication 2006), it turns out that the difference of the mean temperatures during flood and ebb are similar to those presented here (cf. Fig. 9g). And at that pile, no residual volume transport is present. Hence, the heat loss in summer appears to be a general feature of tidal flats. In addition, to demonstrate that equilibrating the ebb and flood flows is a reasonable method, the above calculations were repeated but without equilibration. In that case, the heat flux density at the bADCP averaging over the entire observation period increased from 31 Wm^{-2} (see above Section 4.2) to more than 750 Wm^{-2} . In the same way at the pile, the corresponding value changed from -24 Wm^{-2} (cf. Section 4.3) to about 730 Wm^{-2} . Both values are absolutely unrealistic.

The question arises of the representativity of the results presented here, compared to other regions and other years. For the East Frisian Wadden Sea, heat budget calculations are presently carried out at GKSS, and for the Dutch and Danish Wadden seas, no such investigations are known to the authors. However, the direct observations of the

Figure 14: Mean net heat exchange Q_{mean} over one tide and averaged over one tropical month at the measuring pile in the years 2002, 2003, and 2004. The bold line is that from Fig. 9f.

bottom heat flux of Andrews (1980) were carried out in Ems/Dollart estuary close to the Dutch/German border confirming to a high degree the results of the analytical model of the bottom heat flux presented in this article. Concerning interannual variations, the above calculations were repeated with Hörnum pile data for the previous two years but using the volume flux calibration of 2004. This is critical because the vertical distance between the pADCP and the bottom may be slightly different from year to year and the calibration would not hold; however, the 2002 and 2003 results (Fig. 14) exhibit large similarities with the corresponding 2004 time series, which is another indication that the findings presented are typical features valid for any year. The striking similarity is the sign change of Q_{mean} which consistently occurs at the end of August in all years.

5.5 Outlook

Originally in 2001 when the launch of the bADCP and the measuring pile was planned, it was not the intent to calculate heat budgets or even bottom fluxes in the Wadden Sea. Therefore it was just a matter of luck that both systems were positioned in a way that they revealed the different regimes. As the bADCP belongs to one regime and the pile to the other one, it would be desirable to find out whether a location exists in the Hörnum deep somewhere between the bADCP and the pile where the net heat flux is zero. In the same way, it would also be of interest to discover whether the differences between the positions became more pronounced, e.g. if the pile would be positioned more upstream or the bADCP more downstream. There is also a demand for observations in winter. In addition to shed more light on the matter, direct observations of the bottom heat flux and components of the air-sea heat fluxes would be extremely helpful to confirm some of the above findings.

The method presented encourages the authors to test whether it functions not only for budgeting heat, but also for freshwater and suspended particulate matter. This would enable far reaching statements concerning the erosion and deposition of matter in the Wadden Sea.

6 Conclusions

The heat budget and bottom heat fluxes for a tidally controlled area in the German Wadden Sea (Hörnum Basin) were determined by indirect methods from long-term measurements of water temperature and velocity. Two acquisition systems, a bottom mounted Acoustic Doppler Current Profiler (bADCP) and a measuring pile, were launched at choke points about 4.6 km apart in the same tidal channel, the pile being positioned closer to the shore (upstream). In order to calculate advective heat fluxes, the velocity measurements were calibrated with volume fluxes obtained from ship borne ADCP.

For both devices, the heat budget was evaluated in terms of the residual heat integrated over one tidal cycle, being identical with the combined air-sea heat flux and the flux between the water column and the seabed in the respective catchment areas. According to the analyses for the year 2004, in the catchment area of the bADCP the sea was gaining heat from early spring through late August at an average rate of 31 Wm^{-2} , while the corresponding number for the catchment area of the pile was -24 Wm^{-2} (heat loss). Later on in fall, the heat budget changed sign for both observation sites. Comparisons with other years and other areas suggest that this heat flux scheme is general for Wadden Sea areas. Further investigations lead to the conclusion that the observed differences are due to asymmetries of the heat budget during day and night tidal cycles, which were more pronounced at the pile. These asymmetries can be explained by different exposure times of the tidal flats to the atmosphere at low tide, and subsequent different heat fluxes between the water and the seabed when the flats are flooded.

The bottom heat flux is modelled in terms of a simple analytical relationship between the catchment areas, and the fluxes of volume and heat at the choke points. It clearly shows in agreement with direct observations that the seabed on tidal flats cools the water in spring and summer and heats it in the fall.

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Glossary

symbol	meaning	units
a	ratio of exchanged volume and total volume at the bADCP	
a_0, a_1	regression coefficients	$\text{m}^3 \text{s}^{-1}$
A_0	unit surfac	m^2
A_1, A_2	tidal flat area in the catchment area of the bADCP and the pile, respectively	m^2
ADCP	acoustic doppler current profiler	N/A
ADV	acoustic doppler velocimeter	N/A
b	ratio of exchanged volume and total volume at the pile	
bADCP	bottom mounted ADCP	N/A
C	correlation coefficient	
c_p	specific heat of sea water	$\text{J kg}^{-1} \text{K}^{-1}$
$\Delta Q_1, \Delta Q_2$	heat content change of particles passing the bADCP and the pile, respectively	J
Δt	time difference	s
F_V	volume flux	$\text{m}^3 \text{s}^{-1}$
h	height	m
P_1, P_2	probability that a particle passing the bADCP or the pile reaches a tidal flat	
pADCP	pile mounted ADCP	N/A
q	heat budget	W
q_a	advective heat flux	W
q_{at}	atmospheric heat flux	W
q_b	bottom heat flux	W
q'_b	bottom heat flux density	Wm^{-2}
q_i	internal production of thermal energy	W
q_{lh}	latent heat flux	W
q_{lw}	long wave radiative heat flux	W
q_{sh}	sensible heat flux	W
q_{sw}	short wave radiative heat flux	W
Q	heat	J
Q_{cum}	cumulative heat	J
Q_{mean}	mean heat	J
Q_{mix_1}, Q_{mix_2}	heat exchange by turbulent mixing for a particle passing the bADCP or the pile	J
Q_{tide_1}, Q_{tide_2}	heat gain/loss over one tide for water passing the bADCP or the pile	J
R_1, R_2	residence time on a tidal flat of a particle passing the bADCP or the pile	s
RV	research vessel	N/A
ρ	density of sea water	kg m^{-3}
t	time	s
t_0	starting time	s
t_{arr_1}, t_{arr_2}	arrival time on a tidal flat of a particle passing the bADCP or the pile	s
t_{dep_1}, t_{dep_2}	departure time from a tidal flat of a particle passing the bADCP or the pile	s
t_e	point in time during ebb	s
t_f	point in time during flood	s
t_{low}	time of low tide	s
t_{low}^+	time of ensuing low tide	s
t_{high}	time of high tide	s
t_{high}^+	time of ensuing high tide	s
T	temperature	K
τ	tidal period	s
UTC	Universal Time Coordonné	N/A
V_0	unit volume	m^3
V_1, V_2	volumes exchanged at the pADCP or the pile during one tidal cycle	m^3
vADCP	vessel mounted ADCP	N/A
V_{cum}	cumulative volume exchange	m^3