The Competing Effects of Breaking Waves on Surfzone Heat Fluxes: Albedo vs. Wave Heating

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Key Points:

• Surfzone breaking waves heat via dissipation. Foam increases albedo, reducing solar radiation.

• Over a year, the albedo-induced solar heating reduction was most significant.

• The net effect depends on incident wave height, latitude, seasons, beach slope, and cloudiness.

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Abstract

Depth-limited wave breaking modifies the heat flux in the surfzone relative to the inner-shelf (where waves are not breaking). Surfzone wave breaking generates heat through viscous dissipation (wave heating), but also increase surface foam coverage and albedo, thereby reducing solar heating, i.e., cooling relative to the inner-shelf. These two competing breaking wave effects are quantified with a year-long experiment at the Scripps Institution of Oceanography Pier. Cross-shore averaged surfzone albedo estimates were more than 3 times higher than inner-shelf albedo, reducing the yearly-averaged surfzone water-entering shortwave radiation by 41 W m$^{-2}$ relative to the inner-shelf. Surfzone breaking wave dissipation added an additional yearly-averaged 28 W m$^{-2}$ relative to the inner-shelf. The albedo-induced solar heating reduction in spring, summer and fall was usually greater than the wave heating. However, in winter, large waves and relatively weak shortwave solar radiation (due to both lower top of the atmosphere solar radiation and clouds) resulted in a nearly equal number of days of breaking-wave induced heating or cooling. These two heat flux terms are coupled via wave breaking dissipation. Averaged over the surfzone, the albedo-induced solar radiation reduction is linearly related to the downwelling solar radiation, and is independent of wave height. Consequently, the albedo-induced cooling to wave heating ratio is a function of breaking wave height to the -$3/2$ power, allowing evaluation of the relative importance of these terms in other geographic regions.

1 Introduction

The surfzone (region of depth-limited wave breaking) and adjacent offshore shallow inner-shelf (no depth-limited wave breaking) comprise the nearshore; a physically dynamic, economically important and biologically diverse part of the ocean. Temperature is an important physical attribute here, as temperature variation affects growth rates, recruitment rates and egg mass production rates of various species [e.g., Phillips, 2005; Fischer and Thatje, 2008; Broitman et al., 2005] as well as pathogen ecology [e.g., Goodwin et al., 2012]. Pathogen mortality is related to both temperature [Surbeck, 2009] and exposure to solar shortwave radiation [e.g., Sinton et al., 1999; Boehm et al., 2002; Sinton et al., 2002]. In the nearshore, temperature can also be a tracer for nutrient delivery [e.g., Omand et al., 2012] or surfzone to inner-shelf water mass exchange [e.g., Hally-Rosendahl et al., 2014].
Consequently, quantitatively understanding physical mechanisms affecting the inner-shelf heat budget has been an active area of recent study. Inner-shelf heat budgets include upwelling [e.g., Lentz, 1987; Fewings and Lentz, 2011], wind stress [e.g., Austin, 1999], eddies [e.g., Wilkin, 2006], internal waves [e.g., Shroyer et al., 2010] and the passage of weather systems on time-scales of days to weeks [e.g., Austin and Lentz, 1999]. Heat transfer between the air-sea interface occurs through radiative solar shortwave heating, net long-wave heat flux, as well as net latent and sensible heat exchange, and are often parameterized [e.g., Fairall et al., 1996; Beardsley et al., 1998; Fairall et al., 2003] when applied to observational and modeling studies [e.g., Lentz, 1987; Wilkin, 2006; Etter et al., 2004; Davis et al., 2011].

Closer to shore, rip currents (narrow wave-driven ejections from the surfzone) have been associated with strong temperature variation on the inner-shelf [Smith and Largier, 1995; Hally-Rosendahl et al., 2014], interacting with and adjusting the vertical temperature profile and influencing the inner-shelf cross-shore heat flux [Kumar and Feddersen, 2017]. Thus, surfzone temperature (relative to the stratified inner-shelf) is an important determining factor for how this transport mechanism is established and evolves. Additionally, the presence of fecal indicator bacteria (FIB) near the Southern California coast varies with temperature [Boehm et al., 2004], and predictive models for pathogen transport in the surfzone include temperature and shortwave radiation [e.g., Boehm, 2003]. In addition, solar-radiation induced Enterococcus (FIB) mortality contains cross-shore variation, and modeled FIB concentrations and decay rates were best predicted when cross-shore mortality gradients were included [Rippy et al., 2013]. Thus, cross-shore variation of temperature and solar radiation affect many important biological processes, motivating a more complete understanding of surfzone to inner-shelf temperature and solar radiation differences.

Many aspects of the surfzone heat budget are similar to the inner-shelf heat budget, although the surfzone wave-breaking modify terms and create a new term. The new term, “wave heating” is generated by surfzone wave breaking, which through viscous dissipation, generates heat. Second, breaking-wave induced foam increases the surfzone albedo and thereby reduces the water entering solar shortwave radiation relative to the inner-shelf. Surfzone wave breaking also affects the surfzone sensible [MacMahan et al., 2018] and potentially the latent air-sea fluxes. Here, the wave heating and surfzone foam albedo effects are explored.
The wave heating contribution to the surfzone heat budget results from mechanical wave energy being converted to heat (internal energy) through viscous dissipation. Waves outside the surfzone shoal and break in the shallow surfzone, generating turbulent kinetic energy. Some wave energy is reflected from the shoreline, however on shallow sloping beaches (such as in this study) the percentage of reflected wave energy is typically small (< 3%) [Elgar et al., 1994]. Additional export of mechanical energy from the surfzone (via rip currents or undertow, for example) has been estimated to be many orders of magnitude smaller than incident wave energy flux on similar beaches [Sinnett and Feddersen, 2014]. Other surfzone processes driven by wave-breaking (e.g., alongshore currents, sediment suspension, bubble and spray production) are frictionally balanced, and thus the energy pathway still results in viscous heating. Thus, the bulk of the incident wave energy is dissipated in the surfzone through turbulence throughout the water column, and eventually converted to heat. Wave heating heats the surfzone relative to the inner-shelf.

Solar heat flux is a major surfzone heat budget term [Sinnett and Feddersen, 2014], so changes to the albedo, and thus the amount of absorbed solar radiation, are consequential. The surfzone surface is a combination of foam-free and foam covered areas due to the recent passage of breaking waves [e.g., Frouin et al., 1996]. As foam has a higher albedo (\(\alpha \approx 0.55\) [Whitlock et al., 1982]) than foam free water (\(\alpha \approx 0.06\) [Payne, 1972]), the average albedo is higher in the surfzone than in the relatively foam-free inner-shelf [Frouin et al., 1996]. Deep-water albedo parameterizations have been developed for wind-generated whitecapping [e.g., Koepeke, 1984; Frouin et al., 1996; Jin et al., 2011]. However surfzone foam is due to depth-limited wave breaking and does not require wind, making these parameterizations inappropriate for the surfzone. Recently, a surfzone albedo parameterization has been developed that uses offshore wave conditions, bathymetry, and a surfzone wave model [Sinnett and Feddersen, 2016].

The breaking wave related surfzone albedo increase can be large (as much as 8× the inner-shelf albedo [Sinnett and Feddersen, 2016]) and the subsequent decrease in solar radiation significant. Thus, elevated surfzone albedo results in surfzone cooling relative to the inner-shelf. Similarly, the wave-heating term can be a significant source of heat [Sinnett and Feddersen, 2014]. However, the relative importance of these two competing effects is unknown, as is how parameters such as wave height, beach slope, or latitude affect this. Here, surfzone parameterizations of wave heating [Sinnett and Feddersen,
sen, 2014] and wave-induced albedo increase [Sinnett and Feddersen, 2016] are applied to year-long observations quantifying the affect waves have on the surfzone heat and solar radiation fluxes. The experiment and analysis methods are detailed in section 2. Results quantifying both wave heating and albedo-induced solar heating reduction are described in section 3. Implications for how these two wave-related effects combine to either increase or decrease surfzone heat flux at various other locations and beaches is discussed in section 4. Section 5 is a summary.

2 Methods

2.1 Instrumentation and Data Processing

A yearlong study was conducted at the Scripps Institution of Oceanography (SIO) pier (La Jolla California, 32.867N, 117.257W) between October 25, 2014 and October 25, 2015. The SIO pier extends 322 m west-north-west (288°) from Scripps beach into water depth \( h \approx 7 \) m (Figure 1a). The roughly alongshore uniform shoreline extends 200 m north to 500 m south of the pier. Cross-shore bathymetry profiles were conducted along the pier at 0.5 to 1 month intervals as wave conditions allowed. The cross-shore profile slopes gently with yearly bathymetric changes less than 0.3 m at any location, causing slope variation of less than 5%. The average slope in depths \( h < 3.5 \) m (typically includes the surfzone) is \( s \approx 0.023 \) (Figure 1b). A pier-end NOAA station (9410230) measured 6-min averaged tidal elevation \( \eta \) relative to the mean tide level (MTL). The cross-shore \( x \) coordinate is positive onshore, with the mean shoreline (\( x = 0 \)) where MTL intersects the mean bathymetry. The alongshore coordinate \( y \) is positive toward the north, with \( y = 0 \) at the northern edge of the pier.

For the 365 days beginning October 25, 2014, hourly significant wave height \( H_s \) (zeroth moment of the hourly energy spectrum) and peak period \( T_p \) (period of the highest spectral energy density) were observed at the pier-end (square, Figure 1a and b) by the Coastal Data Information Program (CDIP) station 073 pier-mounted Paros pressure sensor. When the sensor was inoperative (<7% of the time), a spectral refraction wave model with very high skill and initialized from offshore buoys was used [O’Reilly and Guza, 1991, 1998; O’Reilly et al., 2016].

Concurrently, a Campbell Scientific NR01 four-way radiometer located mid-pier (triangle, Figure 1a and b) recorded one-minute averaged downwelling \( Q_{sw}^d \), and reflected
Figure 1. (a) Google earth image of the SIO pier experiment site near mid-tide with the \( x \) and \( y \) coordinates indicated. Locations of the wave and tide gauges (square) and radiometer (triangle) are shown relative to the pier. The surfzone width \( L_{sz} \) (white dotted) extends from the offshore limit of breaking \( x_{sz} \) to the effective shoreline \( x_{sl} \) where \( h = 0 \) 28 m depth. (b) Cross-section along the SIO pier depicting mean tide level (MTL) and mean bathymetry \( z = -h(x) \) versus cross-shore coordinate \( x \) with wave gauge (square) and radiometer (triangle) locations indicated. The radiometer elevation above MTL is \( z = 6.5 \) m (not to scale in b).

upwelling \( Q_{sw}^{u} \) solar shortwave radiation (wavelengths 300 nm to 2800 nm) as described in Sinnett and Feddersen [2016]. Although the radiometer was cleaned at regular intervals, rain or very dense fog caused water to accumulate on the glass optics. Additionally, rarely occurring extremely low tides moved the shoreline seaward of the radiometer location so that the sensors viewed sand rather than water. Data during these times were flagged and removed from the record (6% of all data). For this study, radiation data was hourly-averaged onto the same temporal grid as the wave observations. These wave and radiation data were used to calibrate a parameterization relating offshore wave energy to surfzone albedo as described in section 2.2.3 and detailed in Sinnett and Feddersen [2016].
2.2 Analysis

2.2.1 Wave Model

The cross-shore transformation of normally-incident narrow-banded waves on along-shore uniform beaches is described by one-dimensional wave and roller transformation models [e.g., Thornton and Guza, 1983; Battjes and Stive, 1985; Ruessink et al., 2001]. The wave transformation is given by

\[
\frac{d}{dx}(Ec_g) = -\epsilon_b, \tag{1}
\]

where \( E \) is the wave energy density, \( c_g \) is the linear group velocity given by peak period and depth and \( \epsilon_b \) is the bulk breaking wave dissipation. The wave energy density is

\[
E = \frac{1}{16} \rho g H_s^2, \tag{2}
\]

where \( \rho \) is water density, \( g \) is gravity, and \( H_s \) is the significant wave height. The cross-shore wave energy flux at location \( x \) is

\[
F_{\text{wave}}^{(x)} = Ec_g \quad [\text{W m}^{-1}]. \tag{3}
\]

The model adapted here follows Church and Thornton [1993] with standard breaking parameters (\( B = 0.9 \) and \( \gamma = 0.57 \)).

Similarly, the wave roller transformation describes the dissipation along a breaking wave face with energy equation [e.g., Ruessink et al., 2001]

\[
\frac{d}{dx}(2E rc) = -\epsilon_r + \epsilon_b. \tag{4}
\]

Here, \( E_r \) is the roller energy density, \( c \) is the linear phase speed and roller dissipation \( \epsilon_r \) (analogous to foam) is

\[
\epsilon_r = \frac{2gE_r \sin \beta}{c}, \tag{5}
\]

with wave slope \( \beta = 0.1 \) [e.g., Deigaard, 1993; Walstra et al., 1996]. The model boundary conditions are the pier-end year-long hourly \( H_s \) and peak period observations.

An example cross-shore wave transformation over bathymetry is illustrated (for example) on May 5, 2015 at 14:00 PDT (Figure 2a). Observed offshore wave height \( H_s = 1.4 \) m, slightly increases onshore before breaking due to the shallowing bathymetry (black, Figure 2b). Wave set-up and set-down are ignored in the transformation model as these adjustments contribute to a negligibly small variation in shoreline location. As waves break,
Figure 2. Example cross-shore ($x$) hourly-averaged parameters from May 5, 2015 at 14:00 local time. (a) Bathymetry $h(x)$ (solid) and mean water level $\eta$ (dotted), (b) significant wave height $H_s$ (black) and associated cross-shore wave energy flux $F_{\text{wave}}$ from (3) (red), (c) non-dimensionalized roller energy dissipation $\hat{\epsilon}_r$ from (12) and foam fraction $\zeta$ from (13) as black and red respectively, and (d) albedo on the inner-shelf $\alpha_\theta$ and in the surfzone $\alpha_{sz}$ (14). The offshore breaking location $x_{sz} = -170$ m and effective shoreline $x_{sl} = -22$ m (black dashed in b, c and d). The cross-shore averaged surfzone albedo $\langle \alpha_{sz} \rangle = 0.21$ (black dashed) and albedo where waves are not breaking (with clear sky conditions) $\alpha_\theta = 0.04$ are indicated in (d).

$H_s$ decreases from the outer surfzone to the shoreline, also reducing the wave energy flux $F_{\text{wave}}$ (red, Figure 2b).

The outer-surfzone boundary, $x_{sz}$ (vertical dotted in Figure 2b–d) is defined as where breaking wave dissipation is non-negligible and corresponds to the maximum in $H_s$. Wave transformation models are not designed for shallow swash zones. Thus and “effective shoreline,” $x_{sl}$ is defined as the first offshore location where $h > 0.28$ m, where the wave-roller model is still applicable. Waves in water shallower than $h = 0.28$ m are considered swash.
and this region is ignored. The effective surfzone width $L_{sz}$ is

$$L_{sz} = x_{sl} - x_{sz} \text{ [m]}.$$  \hspace{1cm} (6)

For the example in Figure 2, $x_{sz} = -170$ m and $x_{sl} = -22$ m, making the effective surfzone width $L_{sz} = 148$ m.

2.2.2 Wave Heating

Cross-shore wave energy flux is dissipated across the surfzone by breaking (1). Since wave reflection on shallow sloping beaches is small [Elgar et al., 1994] as is export of mechanical energy from the surfzone [Sinnett and Feddersen, 2014], the bulk of the wave energy flux is frictionally dissipated inside the surfzone, eventually as heat. Assuming the surfzone is well mixed, the heating from wave energy flux dissipation occurs over the entire surfzone width. Thus, the cross-surfzone averaged additional heat flux (relative to no wave breaking on the inner-shelf) due to the dissipation of breaking waves is

$$Q_{\text{wave}} = \frac{F^{(x_{sz})}_{\text{wave}} - F^{(x_{sl})}_{\text{wave}}}{L_{sz}} \text{ [W m}^{-2}],$$  \hspace{1cm} (7)

where superscripts indicate the cross-shore flux location. This term $Q_{\text{wave}}$ is denoted “wave heating”. In the example, at $x_{sz}$, $F^{(x_{sz})}_{\text{wave}} = 7500$ W m$^{-1}$ but at $x_{sl}$ $F^{(x_{sl})}_{\text{wave}} = 33$ W m$^{-1}$ (red, Figure 2b) implying that at this example time, there is a 7467 W m$^{-1}$ energy flux convergence in the surfzone (or $\approx 50$ W m$^{-2}$) which is largely viscously dissipated and converted to heat. Over the year, hourly $Q_{\text{wave}}$ is estimated from observed $H_s$ through (7) and (3).

2.2.3 Solar Radiation

Top of the atmosphere shortwave solar radiation ($Q_{\text{sw}}^{\text{top}}$ in Figure 3) is

$$Q_{\text{sw}}^{\text{top}} = S \cos(\theta_s) \Gamma^{-2} \text{ [W m}^{-2}],$$  \hspace{1cm} (8)

where $S$ is the solar constant, $\theta_s$ is the solar zenith angle (sun declination angle from vertical) which varies on diurnal and seasonal timescales, and $\Gamma$ is the ratio of the actual to mean earth-sun separation distance, which varies annually. [e.g., Whitewman and Allwine, 1986]. Atmospheric attenuation and clouds reduce $Q_{\text{sw}}^{\text{top}}$ so that the downwelling radiation at the ocean surface is $Q_{\text{sw}}^{\text{d}} < Q_{\text{sw}}^{\text{top}}$ (Figure 3). The atmospheric reduction in downwelling shortwave solar radiation is defined as

$$\Delta Q_{\text{sw}}^{\text{d}} = Q_{\text{sw}}^{\text{top}} - Q_{\text{sw}}^{\text{d}} \text{ [W m}^{-2}],$$  \hspace{1cm} (9)
Figure 3. Schematic depicting the shortwave solar radiation \( Q_{sw} \) (arrows) at different locations: the top of the atmosphere (dotted line) \( Q_{top}^{sw} \), downwelling to the ocean surface \( Q_{d}^{sw} \), upwelling (reflected) at the ocean surface \( Q_{u}^{sw} \), and water-entering \( Q_{w}^{sw} \). The solar zenith angle is \( \theta_s \).

and indicates atmospheric optical depth or cloudiness. The shortwave albedo (reflectance) of the ocean surface is the ratio of the reflected (upward) solar radiation to the downwelling solar radiation at the ocean surface,

\[
\alpha = \frac{Q_{u}^{sw}}{Q_{d}^{sw}} ,
\]

so that the water-entering shortwave radiation (Figure 3) is

\[
Q_{sw}^{w} = Q_{d}^{sw}(1 - \alpha) \quad [\text{W m}^{-2}] .
\]

Thus, changes to either the available downwelling radiation \( Q_{d}^{sw} \) or the albedo \( \alpha \) affect the water-entering shortwave radiation and thus solar heating.

2.2.4 Inner-shelf and Surfzone Albedo

In direct sunlight, standard non-wave breaking albedo parameterizations depend only on solar zenith angle \( \theta_s \) [Payne, 1972; Briegleb et al., 1986; Taylor et al., 1996]. In diffuse light (defined here when the ratio of atmospheric reduction in shortwave radiation to top-of-atmosphere shortwave radiation \( \Delta Q_{d}^{sw}/Q_{top}^{sw} > 0.5 \)) ocean surface albedo is near 0.06 and no longer depends on \( \theta_s \) [Payne, 1972]. Thus, here, the inner-shelf albedo (where waves are not breaking) \( \alpha_{\theta} \) is defined following Taylor et al. [1996] with specular reflection for \( \Delta Q_{d}^{sw}/Q_{sw}^{w}/Q_{top}^{sw} \leq 0.5 \) (direct sunlight) and in diffuse light (\( \Delta Q_{d}^{sw}/Q_{sw}^{w}/Q_{top}^{sw} > \)
Figure 4. Yearlong time series of (a) daily maximum solar radiation at the top of atmosphere \( \max(Q_{\text{sw}}^{\text{top}}) \) (red) and hourly averaged downwelling shortwave solar radiation to the ocean surface \( Q_{\text{sw}} \) (black), (b) daily percent reduction of downwelling solar shortwave radiation due to cloud cover \( \Delta Q_{\text{sw}}/Q_{\text{sw}} \), (c) pier-end significant wave height \( H_s \), and (d) surfzone width \( L_{\text{sz}} \) (6).

Seasons denoted in (a) are 91 days long, centered on each solstice and equinox. Data in (a) is removed when rain obscured the radiometer.

0.5 \( \approx 0.06 \) [Payne, 1972]. Latitude and local time define \( \theta_s \) following Reda and Andreas [2008].

In the surfzone, however, albedo is also dependent on the amount of surface foam present due to the passage of breaking waves. Following Sinnett and Feddersen [2016], foam fraction \( \zeta \) is a function of the non-dimensionalized wave roller dissipation \( \hat{\epsilon}_r \),

\[
\hat{\epsilon}_r = \frac{\epsilon_r}{\rho(gh)^{3/2}}.
\]
where non-dimensionalization is denoted with ($\hat{\cdot}$). The example cross-shore $\hat{\epsilon}_r$ profile (black, Figure 2c) has peaks where waves are breaking over shallowing bathymetry and troughs where bathymetry is flatter or wave height is very low. Over the range of $\hat{\epsilon}_r$ typically observed at this location, the foam fraction $\zeta$ and $\hat{\epsilon}_r$ are linearly related [Sinnett and Feddersen, 2016] so that

$$\zeta(x) = m\hat{\epsilon}_r(x), \quad (13)$$

where, $m = 398$ is a constant best-fit parameter. The example cross-shore $\zeta$ profile (red, Figure 2c) includes locations near $x = -75$ m and $x = -40$ m that are nearly continuously covered in foam, while only a few (large) waves break seaward of $x = -150$ m reducing $\zeta$. Under extremely energetic wave conditions, parts of the surfzone can saturate so that the fit produces $\zeta > 1$. When this occurs (less than 4% of the time) the foam fraction is restricted to the physical maximum $\zeta = 1$.

The wave affected (surfzone) albedo $\alpha_{sz}$ has contributions from both the foam-covered and foam-free surface, making

$$\alpha_{sz}(x) = \zeta(x)\alpha_f + (1 - \zeta(x))\alpha_\theta, \quad (14)$$

(Figure 2d). Here, the bet-fit $\alpha_f = 0.465$ [Sinnett and Feddersen, 2016] and $\alpha_\theta$ is the $\theta_s$ parameterized albedo of foam-free water [Taylor et al., 1996]. Onshore of the outer surfzone limit ($x_{sz}$, where waves begin to break) albedo increases above $\alpha_\theta$ due to surface foam. Generally, albedo increases as the surfzone depth decreases, with variation caused by undulations in bathymetry. In the very shallow inner-surfzone, nearly all waves are breaking and the surfzone is nearly saturated in foam, so that $\alpha_{sz} \approx \alpha_f$.

The cross-shore surfzone average foam fraction is

$$\langle \zeta \rangle = \frac{1}{L_{sz}} \int_{x_{sl}}^{x_{sz}} \zeta \, dx, \quad (15)$$

which with (14) yields a cross-shore average surfzone albedo $\langle \alpha_{sz} \rangle$,

$$\langle \alpha_{sz} \rangle = \langle \zeta \rangle \alpha_f + (1 - \langle \zeta \rangle)\alpha_\theta. \quad (16)$$

Here, $\langle \cdot \rangle$ indicates cross-shore averaging. From (11), the surfzone averaged albedo-induced solar heating reduction relative to the inner-shelf is then

$$\Delta Q_{sw}^w = Q_{sw}^d (\alpha_\theta - \langle \alpha_{sz} \rangle) \quad [\text{W m}^{-2}]. \quad (17)$$
Both the amount of available downwelling radiation $Q_d^{sw}$ and the albedo difference between the surfzone and inner-shelf affect $\Delta Q_{sw}^w$. As $\langle \alpha_{sz} \rangle > \alpha_{\theta}$, the surfzone has an albedo-induced cooling relative to the inner-shelf. Over the year, hourly $\Delta Q_{sw}^w$ is estimated with $H_s$ and $Q_d^{sw}$ via (17).

### 3 Observations and Results

#### 3.1 Observed $Q_d^{sw}$, $H_s$, $F_{wave}$ and Albedo

The top of the atmosphere $Q_{sw}^{top}$ varies with $\theta_s$ and $\Gamma$ on diurnal and seasonal time scales, so that the daily maximum $Q_{sw}^{top}$ varies seasonally (red, Figure 4a). At the water surface available downwelling solar radiation $Q_d^{sw}$ primarily varied diurnally, but also varied at synoptic to seasonal time scales (black, Figure 4a). On clear days, atmospheric attenuation resulted in $\Delta Q_d^{sw}/Q_{sw}^{top} \approx 0.25$. Clouds decreased the available $Q_d^{sw}$ further (Figure 4b). In winter, cloudy periods usually lasted a few days (jagged peaks, Figure 4b) and were frequently accompanied by rain causing short $Q_d^{sw}$ data gaps. In the very late spring and early summer, coastal fog persisted for longer periods causing $\Delta Q_d^{sw}/Q_{sw}^{top}$ to remain elevated (Figure 4b). Early spring, late summer and early fall were typically less cloudy.

Pier-end significant wave height $H_s$ typically varied synoptically between 0.5 m and 1.5 m, with generally larger waves in winter and spring, and smaller waves in summer and fall (Figure 4c). Pier-end peak wave period was usually between 7 s and 13 s (not shown). The mixed barotropic tide typically varied $\pm 1$ m (not shown) inducing a roughly $\pm 43$ m variation in $x_{sl}$. Wave and tide conditions, together with the evolving bathymetry, affected the surfzone width $L_{sz}$ (Figure 4d). Average $L_{sz} = 84$ m, but was at times above 150 m during strong wave events and as small as 4 m when waves were small. Time periods were excluded from analysis when waves were very small and $x_{sz}$ was in less than 0.5 m depth (i.e., $L_{sz} < 10$, less than 0.2% of all data).

At the outer surfzone boundary, wave energy flux mean and standard deviation $F_{wave}^{sz}$ = $2149 \pm 1826 \text{ W m}^{-1}$ driven primarily by variable $H_s$ through (3) on synoptic time scales (Figure 5a). Large wave events have an outsized contribution to $F_{wave}$ due to the quadratic relationship between $F_{wave}$ and $H_s$ (3). Seasonal $H_s$ variability generally elevated $F_{wave}$ in wintertime and reduced $F_{wave}$ in summertime. The cross-shore average surfzone albedo mean and standard deviation $\langle \alpha_{sz} \rangle = 0.28 \pm 0.07$ (Figure 5b) and was more than 3 times
Figure 5. Hourly (a) pier-end wave energy flux $F_{\text{wave}}$ (3) and (b) cross-shore averaged surfzone albedo $\langle \alpha_{sz} \rangle$ (16) versus time of year.

The daylight variation of $\langle \alpha_{sz} \rangle$ and $\alpha_\theta$ is examined with ensemble averages. Albedo estimates are removed when solar zenith angle is large ($|\theta_s| > 80^\circ$) to remove near-horizon effects. For each day, the daylight albedo estimates are normalized onto a standard 12 h time-period removing seasonal daylight variations. These are subsequently binned over all the days in the year, allowing inter-day surfzone and inner-shelf albedo comparison. Daily ensemble averaged $\alpha_\theta$ (blue line, Figure 6) has strong solar zenith angle $\theta_s$ dependence, with elevated albedo at low sun angles near sunrise and sunset. Seasonal variation in $\theta_s$ and cloud cover variation account for the relatively small $\alpha_\theta$ deviation from the mean (blue shaded). As the surfzone has fractional foam coverage, $\langle \alpha_{sz} \rangle$ retains some $\theta_s$ dependance, although weaker than $\alpha_\theta$, with elevated $\langle \alpha_{sz} \rangle$ at larger $|\theta_s|$ (red line, Figure 6). However, surfzone foam elevates $\langle \alpha_{sz} \rangle$ above $\alpha_\theta$, with mid-day ensemble averaged $\langle \alpha_{sz} \rangle$ elevated by 0.19 over $\alpha_\theta$. Wave, tide and bathymetry variability influence $\langle \zeta \rangle$ and thus contributes to the relatively large $\langle \alpha_{sz} \rangle$ variability (red shaded).
Figure 6. Daily ensemble averaged albedo with no wave breaking $\alpha_\theta$ (blue) and daily ensemble averaged cross-shore averaged surfzone albedo $\langle \alpha_{sz} \rangle$ (red) versus normalized time of day. Shading is $\pm$ one standard deviation from the mean.

3.2 Competing Wave Effects: $\Delta Q_{sww}^w$ and $Q_{wave}$

Breaking wave energy dissipation leads to surfzone wave heating $Q_{wave}$ (7). Wave breaking also increases albedo, thereby reducing the water-entering shortwave solar radiation relative to the inner-shelf by an amount $\Delta Q_{sww}^w$ (17). Here, these two competing effects are examined. Variability in $Q_{wave}$ and $\Delta Q_{sww}^w$ occur on seasonal, synoptic, diurnal and semi-diurnal timescales through variation in $H_s$, $\theta_s$, $Q_{dsw}^d$ and $L_{sz}$. Here, $Q_{wave}$ and $\Delta Q_{sww}^w$ are daily (24 h) averaged to examine their relative effects on synoptic and seasonal timescales. Henceforth all “Q” variables will be daily-averaged.

Breaking-wave related heat-flux contributions varied over the year (Figure 7) with $Q_{wave}$ always increasing (positive) surfzone heat flux and $\Delta Q_{sww}^w$ always reducing (negative) surfzone heat flux relative to the inner-shelf. Over the year, the mean and standard deviation of the daily-averaged $Q_{wave} = 28 \pm 11 \text{ W m}^{-2}$ (red) and $\Delta Q_{sww}^w = -41 \pm 16 \text{ W m}^{-2}$ (blue). Thus, at this location, the combined effect of $Q_{wave}$ and $\Delta Q_{sww}^w$ typically reduced the surfzone heat flux relative to the inner-shelf. Both daily-averaged $Q_{wave}$ and $\Delta Q_{sww}^w$ varied on synoptic to seasonal time-scales. However, daily averaged $Q_{wave}$ and $\Delta Q_{sww}^w$ were uncorrelated ($r^2 = 0.04$) as $Q_{wave}$ depends on incident $H_s$ (Figure 4c) whereas $\Delta Q_{sww}^w$ depends also on clouds and $Q_{top}^{swp}$. Throughout most of summer, clouds reduced $Q_{dsw}^d$ and waves were small (Figure 4a-c). Thus, the yearly maximum $|\Delta Q_{sww}^w|$ occurred
Figure 7. Yearlong time series of daily (24-hour) averaged wave-heating $Q_{\text{wave}}$ (7) and albedo-induced solar heating reduction $\Delta Q_{\text{sw}}^\text{albd}$ (17) as indicated in the legend.

in April when waves were larger and cloudiness lower, rather than at the summer solstice (21 June) when $Q_{\text{sw}}^\text{top}$ is maximum.

The relative effects of $Q_{\text{wave}}$ and $\Delta Q_{\text{sw}}^\text{albd}$ have a seasonal dependance (Figure 8). In winter, $Q_{\text{sw}}^\text{top}$ is low and cloudiness $\Delta Q_{\text{sw}}^\text{albd}/Q_{\text{sw}}^\text{top}$ can be high reducing $|\Delta Q_{\text{sw}}^\text{albd}|$. Wintertime waves are also relatively large with $Q_{\text{wave}} > 40$ W m$^{-2}$ about 20% of the time. The combined effect in winter heats the surfzone (to the right of the 1:1 line) relative to the inner-shelf 47% of the time (Figure 8a). In contrast, summertime waves were relatively small with $Q_{\text{wave}} > 40$ W m$^{-2}$ only 5% of the time. The combined effect in summer cools the surfzone relative to the inner-shelf 96% of the time (Figure 8c).

Spring is characterized by a wide range of both $Q_{\text{wave}}$ and $\Delta Q_{\text{sw}}^\text{albd}$ (Figure 8b). Spring had few clouds, with $\Delta Q_{\text{sw}}^\text{albd}/Q_{\text{sw}}^\text{top}$ > 40% only a quarter of the time (compared to over half the time in summer). Spring also contained some of the largest $H_s$, resulting in the daily-averaged $Q_{\text{wave}} > 50$ W m$^{-2}$ 11% of the time. The fall $\Delta Q_{\text{sw}}^\text{albd}$ distribution is slightly lower than in summer (Figure 8d). Fall $Q_{\text{sw}}^\text{top}$ is smaller than in summer (red, Figure 4a), yet fall skies were clearer (lower $\Delta Q_{\text{sw}}^\text{albd}/Q_{\text{sw}}^\text{top}$) relative to summer such that mean $Q_{\text{sw}}^\text{albd}$ was reduced by only 5%. Occasional large wave events in late fall (more typical of winter conditions) widened the fall $Q_{\text{wave}}$ distribution compared to summer. The seasonal variation in the $Q_{\text{wave}}$ and $\Delta Q_{\text{sw}}^\text{albd}$ relationship demonstrates the effect of parameters such as the incident $H_s$, cloudiness, and $Q_{\text{sw}}^\text{top}$. 

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As temperature is relevant circulation dynamics, cross-shore exchange, and ecology, relating $Q_{\text{wave}}$ and $\Delta Q_{\text{sw}}^w$ to an adiabatic temperature change is useful for understanding their relative effects. Relative to the inner-shelf, the daily-averaged combined surfzone heat flux $Q_{\text{net}}$ is

$$Q_{\text{net}} = Q_{\text{wave}} + \Delta Q_{\text{sw}}^w \quad [\text{W m}^{-2}],$$

with positive $Q_{\text{net}}$ implying surfzone warming relative to the inner-shelf. For a planar beach slope, the surfzone daily adiabatic temperature change $\Delta T$ induced by $Q_{\text{net}}$ is

$$\Delta T = \frac{t_{\text{day}} Q_{\text{net}}}{1/2 h_{sz} \rho c_p} \quad [^\circ\text{C}],$$  

(18)
Figure 9. Yearly time series of daily adiabatic surfzone temperature change $\Delta T$ (black dots) as in (18) due to the competing wave effects of wave heating $Q_{\text{wave}}$ and albedo-induced solar heating reduction $\Delta Q_{\text{sw}}^{\text{alb}}$. 30-day averages (red dots) and ± standard deviation (red lines), along with the $\Delta T = 0$ (dashed black) are highlighted for reference.

where $t_{\text{day}} = 86400$ s is the duration of a day and $h_{\text{sz}}$ is the outer surfzone boundary depth. Here, the surfzone is assumed adiabatic (insulated) with no other breaking-wave induced heat fluxes (e.g., surfzone to inner-shelf exchange or air-sea fluxes).

Over the year, the daily adiabatic $\Delta T$ (18) was negative 75% of the time (black dots, Figure 9), with a mean and standard deviation of $\Delta T = -0.5 \pm 0.6$ °C. The 30-day $\Delta T$ mean and standard deviation also varied seasonally (red dots and red lines, Figure 9). Wintertime mean and standard deviation $\Delta T = 0.0 \pm 0.4$ °C as wintertime $Q_{\text{net}}^{\text{top}}$ is near zero. Beginning in early spring, $\Delta T$ typically becomes negative, with mean and standard deviation $\Delta T = -0.7 \pm 0.5$ °C between March and September. In late summer and early fall with low clouds and small waves, $\Delta T$ can be as low as $-1.9$ °C. Daily $\Delta T$ variability was largest in spring and late summer when $Q_{\text{sw}}^{\text{top}}$ was high, but intermittent clouds or coastal fog caused large changes in $\Delta Q_{\text{sw}}^{\text{d}}$. The late fall $Q_{\text{sw}}^{\text{top}}$ reduction and overall $H_s$ increase (Figure 4a,c) prompted a return to winter conditions. In the adiabatic limit, net surfzone heat flux changes induced by $Q_{\text{wave}}$ and $\Delta Q_{\text{sw}}^{\text{alb}}$ are substantial and can induce significant ($O(1\,^\circ\text{C})$) temperature changes.
Figure 10. Daily-averaged albedo-induced solar heating reduction $\Delta Q_{sw}^{d}$ (17) versus observed daily-averaged downwelling solar radiation $Q_{sw}^{d}$. Symbols are identified (color and shape) by season. The the best-fit slope of -0.19 (red line) deviates less than 1% from the idealized slope (dashed black line) from (21). The squared correlation $r^2 = 0.48$.

4 Discussion

4.1 Scaling for an idealized surfzone

Parameters affecting surfzone averaged $\Delta Q_{sw}^{w}$ and $Q_{wave}$ are explored with scalings for a constant slope surfzone, lending insight to potential application at other sites with variable $Q_{sw}^{top}$, clouds, incident waves, and beach slope. Although $\Delta Q_{sw}^{w}$ and $Q_{wave}$ are uncorrelated, both depend on incident wave conditions, so a relationship exists between the two with added variability from the other non-wave factors such as bathymetric slope $s$ and downwelling solar radiation at the water surface $Q_{sw}^{d}$. For an idealized surfzone of constant bathymetric slope $s$ and constant $\gamma$, the surfzone averaged foam fraction $\langle \zeta \rangle$ (15) can be related to the non-dimensionalized roller dissipation through (13) by surfzone averaging both the numerator and denominator in (12). The surfzone-averaged $\bar{\epsilon}_r$ is simply $Q_{wave} = F_{wave}/L_{sz}$, and for a planar slope the representative (surfzone averaged) $h_{sz}^{3/2}$ becomes $(2/5)h_{sz}^{3/2}$. Thus bulk surfzone non-dimensional roller dissipation $\langle \bar{\epsilon}_r \rangle$ can be scaled as

$$\langle \bar{\epsilon}_r \rangle = \frac{2}{5} \frac{Q_{wave}}{\rho (g h_{sz})^{3/2}},$$  

(19)
where the outer surfzone boundary depth \( h_{sz} = H_{sb}/\gamma \), \( H_{sb} \) is the significant wave height at breaking, and \( \gamma = 0.57 \) is the breaking parameter. The surfzone averaged foam fraction \( \langle \zeta \rangle \) is found applying (19) to (13) so that

\[
\langle \zeta \rangle = \frac{m Q_{\text{wave}}}{2\gamma (gh_{sz})^{3/2}} = \frac{5}{32} m s \gamma^2,
\]

(20)

where \( m = 398 \). The surfzone-averaged \( \langle \zeta \rangle \) is independent of \( H_{s} \), yet is linearly related to bathymetric slope \( s \). Thus, the ratio of daily averaged \( \Delta Q_{\text{sw}}^w \) and \( Q_{\text{sw}}^d \) is expected to be

\[
\frac{\Delta Q_{\text{sw}}^w}{Q_{\text{sw}}^d} = \langle \zeta \rangle (\bar{\alpha}_\theta - \alpha_I) = \frac{5}{32} m s \gamma^2 (\bar{\alpha}_\theta - \alpha_I),
\]

(21)

where \( \bar{\alpha}_\theta \) is the constant daily averaged albedo of the inner-shelf. For constant \( s \) and \( \gamma \) and daily averaged \( \bar{\alpha}_\theta \), the the daily-averaged \( \Delta Q_{\text{sw}}^w \) and \( Q_{\text{sw}}^d \) is expected to be linearly related.

The daily averaged \( \Delta Q_{\text{sw}}^w \) and \( Q_{\text{sw}}^d \) are linearly related (Figure 10, squared correlated \( r^2 = 0.48 \) \((p < 0.01)\)) with best-fit slope -0.19 (red line). This implies that the daily averaged surfzone albedo is on average 0.19 larger than the inner-shelf. With an idealized (constant) bathymetric slope \( s = 0.023 \), daily-averaged clear-sky inner-shelf albedo \( \bar{\alpha}_\theta = 0.06 \) [e.g., Payne, 1972], and foam albedo \( \alpha_I = 0.465 \) as in section 2.2.4, the surfzone averaged foam fraction (20) applied to (21) yields a theoretical slope \( \langle \zeta \rangle (\bar{\alpha}_\theta - \alpha_I) = -0.19 \) (dashed black line, Figure 10) which is less than 1% different from the best fit slope to observations. Deviations from the scaline (21) are potentially due to tidal and incident \( H_s \) variation together with the realistic and variable non-planar bathymetry. The linear relationship correlation between \( \Delta Q_{\text{sw}}^w \) and \( Q_{\text{sw}}^d \) (Figure 10) that matches the scaling (21) demonstrate the suitability of (20) and (21) to effectively scale \( \Delta Q_{\text{sw}}^w \) on gently sloping and alongshore uniform beaches.

Next, for a planar slope using (21), the ratio of surfzone daily averaged \( \Delta Q_{\text{sw}}^w \) magnitude to \( Q_{\text{wave}} \) is

\[
\left| \frac{\Delta Q_{\text{sw}}^w}{Q_{\text{wave}}} \right| = \left[ \frac{5 m \gamma^{3/2} (\bar{\alpha}_\theta - \alpha_I)}{2 \rho g^{1/2}} \right] \frac{Q_{\text{sw}}^d}{H_{sb}^{3/2}},
\]

(22)

where the bracketed quantity is a constant and is independent of bathymetric slope. Thus the ratio \( \left| \Delta Q_{\text{sw}}^w \right|/Q_{\text{wave}} \) largely depends on \( Q_{\text{sw}}^d/H_{sb}^{3/2} \). The downwelling solar radiation \( Q_{\text{sw}}^d \) depends on cloudiness and top of the atmosphere \( Q_{\text{sw}}^{\text{top}} \). Daily averaged \( Q_{\text{sw}}^{\text{top}} \) is found from (8), and cloudiness (atmospheric attenuation or optical depth) may be estimated from terrestrial or satellite products [e.g., CERES, 2018]. The wave height at the break-
Figure 11. Normalized joint PDF (gray shaded) of daily averaged $|\Delta Q^w_{sw}|/Q_{wave}$ and significant wave height at breaking $H_{sb}$. The $|\Delta Q^w_{sw}|/Q_{wave} = 1$ line is highlighted, delineating relative cooling ($>1$) and heating ($<1$). Daily averaged $|\Delta Q^w_{sw}|/Q_{wave}$ observations at various clear skies (25% atmospheric attenuation), the $|\Delta Q^w_{sw}|/Q_{wave}$ ratio versus $H_{sb}$ is found from (22) and plotted for the summer (solar maximum, solid) and winter (solar maximum, dotted) at the equator ($0^\circ$N), $33^\circ$ and $66^\circ$ latitude (colored). Summer (solid) $33^\circ$ and $66^\circ$ latitude (black and blue) curves are nearly on top of each other.

Point $H_{sb}$ can be well modeled [e.g., Ruessink et al., 2003] given incident wave conditions.

The $|\Delta Q^w_{sw}|/Q_{wave}$ scaling for an idealized surfzone (22) is compared with observations (Figure 11), illustrating how clouds, $Q^d_{sw}$ and $H_{sb}$ affect the $|\Delta Q^w_{sw}|/Q_{wave}$ ratio. The observed $|\Delta Q^w_{sw}|/Q_{wave}$ ratio is largest for small $H_{sb}$ and decreases for larger $H_{sb}$ consistent with the scaling. For $H_{sb} > 1.5$ m, the observations and scaling have $|\Delta Q^w_{sw}|/Q_{wave} < 1$ (relative heating) at this location. For a clear sky (no clouds or constant atmospheric attenuation), $Q^d_{sw}$ in (22) depends only on $Q^\text{top}_{sw}$, varying only by season and latitude. At a latitude of $33^\circ$N (near the SIO pier) for the clear-sky summer sol- lar maximum, the $|\Delta Q^w_{sw}|/Q_{wave}$ scaling (22) bounds the upper limit on the observed $|\Delta Q^w_{sw}|/Q_{wave}$ for a particular $H_{sb}$ (Figure 11, solid black). For the $33^\circ$N clear-sky winter solar minimum, the $|\Delta Q^w_{sw}|/Q_{wave}$ scaling intersects the observations (Figure 11, black
dashed). Without clouds, $|\Delta Q^w_{sw}|/Q_{wave}$ observations are expected to fall between the black solid and dashed curves. However, the presence of clouds lower the observed $Q^d_{sw}$ (and subsequently the $|\Delta Q^w_{sw}|/Q_{wave}$) for a particular $H_{sb}$. Thus, the scaling (22) sets an upper bound.

The scaling for $|\Delta Q^w_{sw}|/Q_{wave}$ (22) can be used for to estimate the relative importance of $|\Delta Q^w_{sw}|/Q_{wave}$ at other locations with variable latitude and seasonal top of the sky, cloud, beach slope and wave conditions. At the equator $0^\circ$N seasonal variation in $Q_{top}^{sw}$ is very small, resulting in a similar clear-sky $|\Delta Q^w_{sw}|/Q_{wave}$ and $H_{sb}$ relationship year-round (red solid and dashed curves in Figure 11). At high latitudes, the seasonal difference in $Q_{top}^{sw}$ is large, expanding the summer to winter difference. At $66^\circ$N, the summer clear-sky $|\Delta Q^w_{sw}|/Q_{wave}$ to $H_{sb}$ relationship (Figure 11, blue solid ) is nearly the same as at $33^\circ$N (the experiment site). However, for wintertime clear skies, $|\Delta Q^w_{sw}|/Q_{wave} \ll 1$ for any $H_{sb} > 0.4$ m (Figure 11, blue dashed) indicating wave heating nearly always dominates. In contrast at $33^\circ$N, wintertime clear sky $|\Delta Q^w_{sw}|/Q_{wave} < 1$ only for $H_{sb} > 1$ m. These significant latitude and season differences in clear-sky $|\Delta Q^w_{sw}|/Q_{wave}$ will have implications for surfzone heat budgets from equator to Arctic.

4.2 Wave heating $Q_{wave}$ and albedo-induced solar radiation reduction
$\Delta Q^w_{sw}$ in context

At the La Jolla, CA experiment site, the parameters $H_s$, $h(x)$, $Q^d_{sw}$, $Q_{top}^{sw}$, and cloudiness ($\Delta Q^d_{sw}/Q_{top}^{sw}$) contribute to the breaking-wave induced positive or negative surfzone heat flux relative to the inner-shelf. Here, the two terms $Q_{wave}$ and $\Delta Q^w_{sw}$ are placed in the context of a previous surfzone heat budget. Including wave-heating ($Q_{wave}$) but not $\Delta Q^w_{sw}$ improved a summer-time binned-mean surfzone heat budget on diurnal and longer time-scales [Sinnett and Feddersen, 2014]. However, here the summer-time $|\Delta Q^w_{sw}|$ was usually greater than $|Q_{wave}|$ (Figure 8c). However, $Q_{wave}$ and $\Delta Q^w_{sw}$ are uncorrelated ($r^2 < 0.04$). Thus, including $Q_{wave}$ but not $\Delta Q^w_{sw}$ still improved the binned mean heat budget slope by reducing the unexplained variance. Sinnett and Feddersen [2014] also inferred a net surfzone cooling of $\approx 5200$ W m$^{-1}$ (or $\approx 90$ W m$^{-2}$ over the average $L_{sz}$ for the same period) required to balance the surfzone heat budget. Here, the summer-averaged $\Delta Q^w_{sw} = 44$ W m$^{-2}$ (compare to the yearly-averaged $\Delta Q^w_{sw} = 41$ W m$^{-2}$) may account for for nearly half the Sinnett and Feddersen [2014] inferred required net cooling. Advective processes, such as transient rip currents [e.g., Hally-Rosendahl et al.,
2015] or nonlinear internal wave runup [e.g., Sinnett et al., 2018] may also contribute
to the required relative surfzone cooling.

Breaking-wave induced changes to the Surfzone latent or sensible heat flux are also
modified by wave-breaking due to surfzone spray and aerosol generation, which may also
contribute to the surfzone heat budget. Parameterized (COARE) surfzone sensible heat
flux estimations required an additional spray contribution when compared to surfzone
covariance measurements [MacMahan et al., 2018]. For the average wave dissipation ob-
served at this site, the additional sensible heat flux due to breaking wave spray is ≈ 5 W m$^{-2}$,
relatively small compared to $Q_{\text{wave}}$ and $\Delta Q_{\text{sw}}^{\text{w}}$ at Scripps Beach. Spray droplets produced
by breaking are typically large [Andreas, 2016] and quickly fall back to the surface be-
fore exchanging latent heat [Veron, 2015; MacMahan et al., 2018]. However, the enthalpy
exchange coefficient may be larger for a foamy sea surface than a foam-free surface [Chick-
apel, 2018], potentially enhancing surfzone latent heat flux. Examination of all surfzone
heat flux terms, is warranted to properly understand all the ways that breaking waves
can affect the surfzone heat budget.

5 Summary

Nearshore heat and solar radiation budgets typically overlook breaking wave ef-
facts, and the relative importance of this adjustment is unknown. Here, the relative ef-
facts of wave heating due to viscous dissipation of breaking waves $Q_{\text{wave}}$ and albedo-induced
solar heating reduction relative to the inner-shelf are studied with year-long observations
at the Scripps Institution of Oceanography (La Jolla CA) pier. Wave energy flux at the
outer surfzone boundary $F_{\text{wave}}^{\text{sz}} = 2149\pm1826$ W m$^{-1}$, which dissipated over $L_{\text{sz}}$ yield-
ing a daily-averaged wave heating contribution $Q_{\text{wave}} = 28\pm11$ W m$^{-2}$. Breaking waves
partially covered the surfzone in foam, increasing albedo on average by a factor of 3 rel-
ative to the inner-shelf. The increased surfzone albedo subsequently created a solar heat-
ing reduction relative to the inner-shelf of $\Delta Q_{\text{sw}}^{\text{w}} = 41 \pm 16$ W m$^{-2}$. Usually at this
location, the net effect ($Q_{\text{wave}} + \Delta Q_{\text{sw}}^{\text{w}}$) together act to cool the surfzone relative to the
inner-shelf. However, the combined ($Q_{\text{wave}}$ and $\Delta Q_{\text{sw}}^{\text{w}}$) effect had seasonal dependence,
with a net heating roughly half the time in winter, but only 4% of the time in summer.

On a beach of constant slope, the average surfzone foam fraction can be scaled as
a function of beach slope, resulting in a surfzone averaged albedo $\langle \alpha_{\text{sz}} \rangle$ that is indepen-
dent of $H_s$. At the experiment site, $\Delta Q_{sw}^w$ and $Q_{sw}^d$ are linearly related and are in good
agreement with the scaling. Scalings also are developed to the relative breaking wave sur-
fzone heat flux contribution. The amount of additional surfzone cooling or heating rel-
ative to the inner-shelf is related to the ratio of $Q_{sw}^d$ to $H_{sl}^{3/2}$ at the outer surfzone bound-
ary. Clouds, $Q_{sw}^{top}$ and $H_{sb}$ affect the $|\Delta Q_{sw}^w|/Q_{wave}$ ratio and thus the relative surfzone
cooling or heating. This scaling can be applied at other locations to determine the rel-
ative heating or cooling effects of surfzone breaking waves.

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