SCALING OF THE SEA-BREEZE STRENGTH WITH OBSERVATIONS IN THE NETHERLANDS

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Abstract. In this study we evaluate recently proposed scaling relations for the sea-breeze strength using independent data for a relatively homogeneous area in The Netherlands. We show that several of the scaling relations in the literature incorporate hidden correlation. Furthermore, it appears that the estimate for the sea-breeze strength is better made on the basis of the time-integrated rather than of the instantaneous sensible heat flux. It also turns out that for similar forcing the sea breeze in The Netherlands is about twice as strong as the sea breeze in the Vancouver area of Canada.

Keywords: Scaling laws, Sea breeze.

1. Introduction

Sea breezes are initiated by differential heating of the air over adjacent land and sea surfaces. As such a pressure gradient across the cold, high-pressure region over water and the warm, low-pressure region over land results. It is found that a sea breeze will generally commence as a light shoreward surface wind, at roughly right angles to the coast, before moving in a clockwise direction (in the Northern Hemisphere, due to the Coriolis force) as the breeze increases in strength. Here, we define the sea-breeze strength as the magnitude of the shoreward component of the wind speed, which mainly depends on the magnitude of the differential heating and the complexity of the coastline (e.g., Tijm et al., 1999a).

Sea breezes have been studied frequently using both mesoscale numerical models and observations. It turns out that some of the characteristics of the sea breeze can be captured in simple scaling laws (e.g., Niino, 1987; Steyn, 1998; Tijm et al., 1999b), which may facilitate practical application in weather forecasting for example. On the basis of Nino (1987), Steyn (1998) presented scaling relations for the sea-breeze strength and depth. These empirical relations were based on dimensionless variables, including the instantaneous surface heat flux over land. Steyn evaluated these scaling relations with observations from the Lower Fraser Valley of British Columbia in rather complex terrain with inhomogeneous surface conditions. Recently, Steyn (2003) presented a revision of his 1998 paper, in which he extends the original sea-breeze scaling with the time-integrated surface heat

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flux over land (following earlier ideas by Tijm and Holtslag as represented in Tijm et al., 1999b). Also dependency on latitude was introduced by incorporating data from two additional locations (for The Netherlands and eastern Spain at 52°N and 36°N, respectively).

In this study, we extend the studies of Steyn (1998, 2003) by analyzing an independent database with hourly measurements for The Netherlands. Note that The Netherlands has a rather dense observation network in a relatively homogeneous area. By doing so we are able to refine the original proposals and we can make a more critical test of the proposals made. We also find that the results of Steyn are influenced by hidden correlation in the scatter plots presented by him. We will show independent tests below.

2. Scaling the Sea-Breeze Strength

Steyn (1998) introduces an empirical relation for the sea-breeze strength. To obtain this relation, a new set of scales for variables relevant in sea-breeze situations is introduced by following an analysis of the governing equations under the Boussinesq approximation (based on Niino, 1987). Nondimensionalization of the governing equations with this new set of scales leads to four dimensionless parameters. Steyn combines these four dimensionless parameters to define empirical relations for sea-breeze strength and depth. For the sea-breeze strength he uses two dimensionless parameters, for the sea-breeze depth only one.

The scaling result of Steyn (1998) for the sea-breeze strength can be written as:

$$\frac{u_{sb}}{u_s} = \alpha_1 \Pi_1^{-1/2} \Pi_4^{1/4} = \alpha_1 \left(\frac{g}{T_0} \frac{(\Delta T)^2}{N\overline{w'T'}} \right)^{-1/2} \left(\frac{N}{\omega} \right)^{1/4}, \tag{1}$$

where u_{sb} is 'a' characteristic wind speed in the sea-breeze layer (Steyn used the average wind speed in the sea-breeze layer in his study), u_s is the horizontal velocity scale defined by Steyn as $g\Delta T/T_0 N$ (this scale represents the rate of work done by buoyancy in driving the sea-breeze flow in an overlying stable atmosphere), α_1 is a coefficient with value 1.10 (Steyn, 1998), Π_1 and Π_4 are dimensionless parameters obtained by nondimensionalization of the governing equations, g is the gravitational constant, T_0 is the temperature at sea level, ΔT is the temperature difference between land and sea surface temperature, N is the Brunt–Vaïsälä frequency of the overlying atmosphere, $\overline{w'T'}$ is the instantaneous sensible heat flux at the earth's surface, and ω is the frequency of diurnal heating.

Steyn (2003) introduces a time-integrated instead of an instantaneous surface sensible heat flux, following ideas by Tijm and Holtslag (as represented in Tijm et al., 1999b). Notice that in Steyn (2003) the exponent of Π_4 has changed to 1/2 (instead of 1/4 in Steyn, 1998). Furthermore, latitude dependency was introduced by incorporating data from two additional locations (for The Netherlands and eastern retirando la cor. oculta

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Spain at 52° N and 36° N, respectively). In the present study we evaluate data for The Netherlands only. For a fixed latitude, we can write Steyn's (2003) relation as:

$$\frac{u_{sb}}{u_s} = \alpha_2 \Pi_{1,i}^{-1/2} \Pi_4^{1/2} = \alpha_2 \left(\frac{g}{T_0} \frac{(\Delta T)^2}{N \frac{1}{t_p - t_s} \int_{t_s}^{t_p} \overline{w'T'} \mathrm{d}t} \right)^{-1/2} \left(\frac{N}{\omega} \right)^{1/4}, \tag{2}$$

$$= g \frac{\Delta T}{T_0 N}$$

where α_2 is a latitude-dependent coefficient with value $0.85\Pi_2^{-9/4}$ (Steyn, 2003). For The Netherlands α_2 becomes 0.31 using a latitude of 52°N. Furthermore $\Pi_{1,i}$ is the dimensionless parameter with the time-integrated sensible heat flux, t_p is the present time (at which sea-breeze measurements are taken), and t_s is the start time (at which the sensible heat flux first becomes positive).

It can be noted that in relations (1) and (2), u_s, Π_1, $\Pi_{1,i}$ and Π_4 contain equal and corresponding terms. The scaling parameter u_s contains $1/\Delta T$, while Π_1 and $\Pi_{1,i}$ contain $[(\Delta T)^2]^{-1/2}$. Besides, u_s contains g, T_0 and N, which return in Π_1, $\Pi_{1,i}$ or Π_4. These equal and corresponding terms lead to hidden correlation in the figures of Steyn. To investigate the effect of this hidden correlation, we rewrite relations (1) and (2) for the sea-breeze strength without corresponding terms in both sides. This provides the following dimensional relationships:

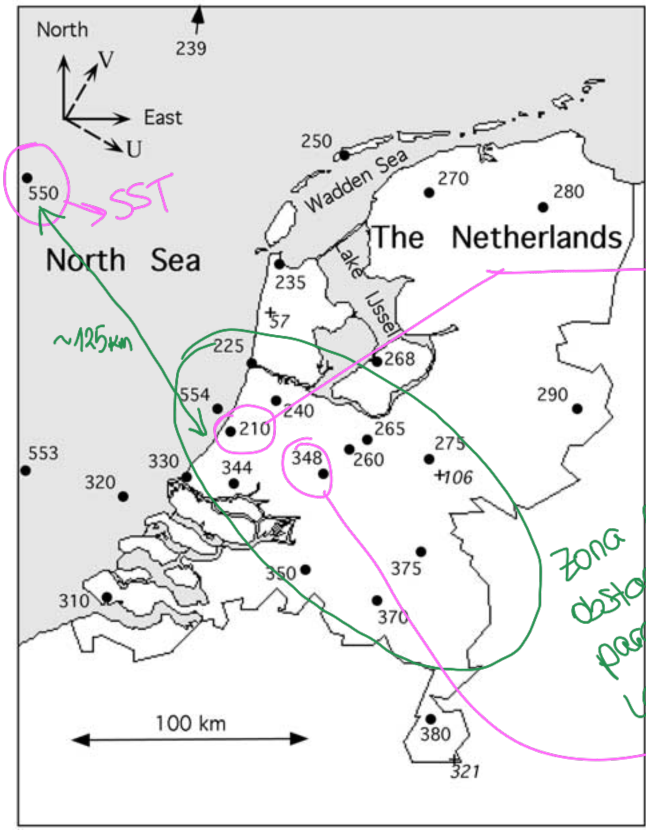
$$u_{sb} = \alpha_3 \left(\frac{g}{T_0} \frac{(\overline{w'T'})}{\omega} \right)^{1/2} \left(\frac{N}{\omega} \right)^{-1/4}, \tag{3}$$

instead of relation (1), and

$$u_{sb} = \alpha_4 \left(\frac{g}{T_0} \frac{\left(\frac{1}{t_p - t_s} \right) \int_{t_s}^{t_p} \overline{w'T'} \mathrm{d}t}{\omega} \right)^{1/2} \tag{4}$$

instead of relation (2).

Note that in relation (4), the dependency on N has disappeared. This implies that, at a fixed latitude, the sea-breeze strength is only a function of the time-integrated sensible heat flux! Similar reasoning can be followed for the dimensionless parameters found for the sea-breeze depth (Steyn, 1998). However, we cannot investigate the latter here due to a lack of measurements of the sea-breeze depth.



P, WD, WS, T.... (hourly)

Zona plana, sin obstaculos. Perfecta para el desarrollo de la brisa.

(Cabauw) SH (30min avg)

Figure 1. Map of the synoptic meteorological measuring stations in The Netherlands.

3. Data

3.1. Area and Measurements

Under clear-sky conditions, The Netherlands is a relatively ideal country for topographically undisturbed sea-breeze studies at mid-latitudes, since the country is flat and rather homogeneous (see Figure 1). A strip of dunes along the coast, about 5 km in width and with a highest peak of 57 m (beyond our area of interest in the north-west of The Netherlands) is the only obstacle the sea breeze experiences on its passage inland, encountering wide grasslands spread out over the countryside with occasional small forests. The average roughness length of this area is about 0.15 m (while the roughness length of the area in the study of Steyn is about 0.5 m). The only hills of any significance (about 100 m in height) are located more than 100 km inland.

In the south-west of the country the coast is rather ragged. Here the rivers Rhine, Maas and Schelde flow into the North Sea. In the north-west the Wadden Islands and Lake IJssel are present. Nevertheless, the area in between is very suitable for sea-breeze studies. Other advantages are the relatively straight north-south oriented coastline and the high density of synoptic meteorological measuring stations. At all these stations the Royal Netherlands Meteorological Institute (KNMI) measures pressure, wind direction, wind speed, temperature and several other variables every hour. In Cabauw (station 348) the sensible heat flux is also directly observed.

For testing the scaling relations, observational data from station 210 and sensible heat fluxes from Cabauw are used. Because of its position far inland, the measured fluxes are representative of the whole area and rather independent of the (developing) sea-breeze circulation (at least until noon). Both stations experience minimal influence from Lake IJssel and the ragged coast in the south-west of the country. Because determination of the Brunt–Väisälä frequency, N, is not straightforward, and because the dependency in relations (1) and (2) is weak, N is taken constant here with a typical value of 0.016 K m^{-1}.

Hourly measurements of temperature, pressure, wind speed and wind direction are available for May 1989, as well as April through August for the years 1994 and 1995. Sensible heat flux is measured every 30 min at station 348 and is available for the same months. These data are converted to hourly averages. Representative sea-surface temperatures are taken from station 550, which is about 125 km from the coast in the North Sea. Sea-surface temperatures are converted into 10-day averages for every hour to minimize the land influence.

3.2. Selection of Sea-Breeze Days

(No utilizan criterio Bourne...)

The following criteria are used to select days with a well-developed sea-breeze circulation from the database. First, the land-sea temperature difference must exceed 5 °C during the daytime. Station 210 is used for the land temperature and station 550 is used for the sea-surface temperature. Second, the shoreward component of the wind speed at the moment of sunrise may not exceed 1 m s^{-1}. The shoreward component of the wind speed must reduce to values below 1 m s^{-1} before sunrise the next day. The shoreward component of the wind speed may not increase at station 348 before it increases at station 210. Days with large-scale frontal passages that meet these criteria are removed manually. From the resulting selection only the best days with a smooth course of the shoreward component of the wind speed are selected. This final selection results in a set of 34 sea-breeze days, on which the relations (1) to (4) are tested.

3.3. Wind Speed Measurements and Interpretation

In the study of Steyn (1998) the average wind speed in the sea-breeze layer is used to define the scaling law for the sea-breeze strength. Due to a lack of wind profile data in our study, the wind speed at 10-m height is used as the representative value. This is allowed if the wind speed at this height, as with the average wind speed in the sea-breeze layer, is characteristic of the sea-breeze strength. Note that the 10-m

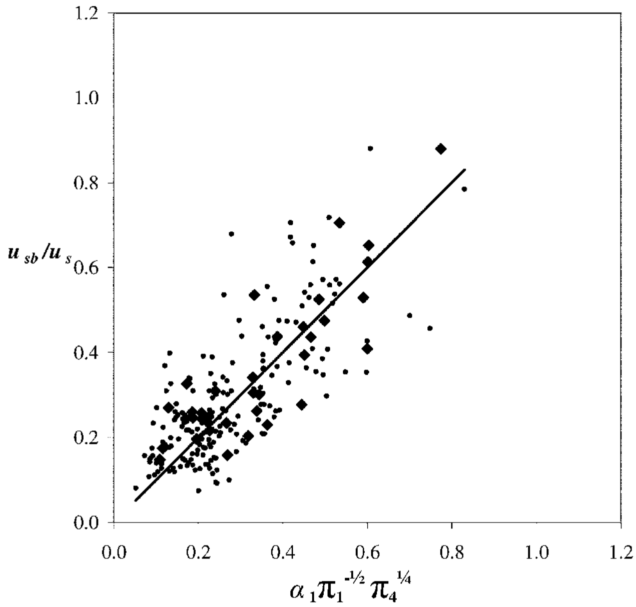


Figure 2. Scatterplot of the scaled sea-breeze strength (u_{sb}/u_s) against $\alpha_1\Pi_1^{-1/2}\Pi_4^{1/4}$, where $\Pi_1 = g(\Delta T)^2/(T_0 N\overline{w'T'})$ and $\Pi_4 = N/\omega$ (relation 1). The dots represent all points prior to maximum sea-breeze strength and the diamonds represent the points at maximum sea-breeze strength.

wind speed in Cabauw is not too different from the typical boundary-layer average in the unstable conditions examined (e.g., Holtslag, 1984).

4. Results

Figures 2 through 5 show comparisons of relations (1)–(4) with the available data. Each dot or square represents a calculation for one hour. In these figures the dots represent the calculations that are made for all hours until the sea-breeze strength is found to be maximal (typically around 1300 UTC). The bold squares represent the calculation of quantities at the time of the maximum sea-breeze strength.

First, Figure 2 shows the scatter plot for relation (1). The value of the coefficient α_1 is 2.44 for the calculations for all hours prior to maximum sea-breeze strength, and α_1 is 3.11 for the calculation at maximum sea-breeze strength. The linear regression coefficients are 0.53 and 0.73, respectively. The standard deviations of estimates of the coefficient in relation (1) are 0.16 and 0.17, respectively.

Figure 3 shows the scatter plot for relation (2). The value of the coefficient α_2 is 0.68 for the calculations with all hours prior to maximum sea-breeze strength, and α_2 is 0.80 for the calculations at maximum sea-breeze strength. The linear

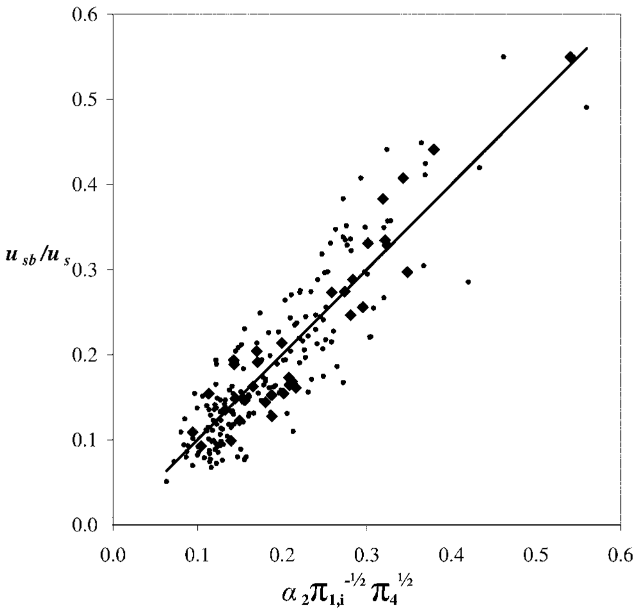


Figure 3. Scatterplot of the scaled sea-breeze strength ($u_{sb,i}/u_s$) against $\alpha_2\Pi_{1,i}^{-1/2}\Pi_4^{1/2}$, where $\Pi_{1,i} = g(\Delta T)^2/(T_0 N H)$ (in which H is the time-integrated sensible heat flux, $H = (\frac{1}{t_p - t_s})\int_{t_s}^{t_p} \overline{w'T'}\mathrm{d}t$) and $\Pi_4 = N/\omega$ (relation 2). The dots represent all points prior to maximum sea-breeze strength and the diamonds represent the points at maximum sea-breeze strength.

regression coefficients are now 0.78 and 0.88, respectively. The standard deviations are 0.09 and 0.10, respectively.

For both relations, we see that the calculations at maximum sea-breeze strength give higher correlation and higher values for the coefficients α_1 and α_2 than the calculations including all hours prior to maximum sea-breeze strength. Furthermore, we note that the relation with the time-integrated surface sensible heat flux, relation (2), indeed gives better results than the original proposal with the instantaneous heat flux, relation (1).

As mentioned in Section 2, hidden correlation occurs in plots such as Figures 2 and 3. In the following figures, we therefore show the results using relations (3) and (4). In these figures, on the x-axis the estimated sea-breeze wind speed is plotted and on the y-axis the observed wind speed. Hence, in these figures there are no equal or corresponding terms on the x- and the y-axes, and the relations that describe the sea-breeze strength are directly tested with observations (without scaling them).

Figure 4 shows the scatter plot for relation (3). It is obvious that the scatter of points has increased considerably. For the calculations with all hours prior to maximum sea-breeze strength, the linear regression coefficient decreases signific-

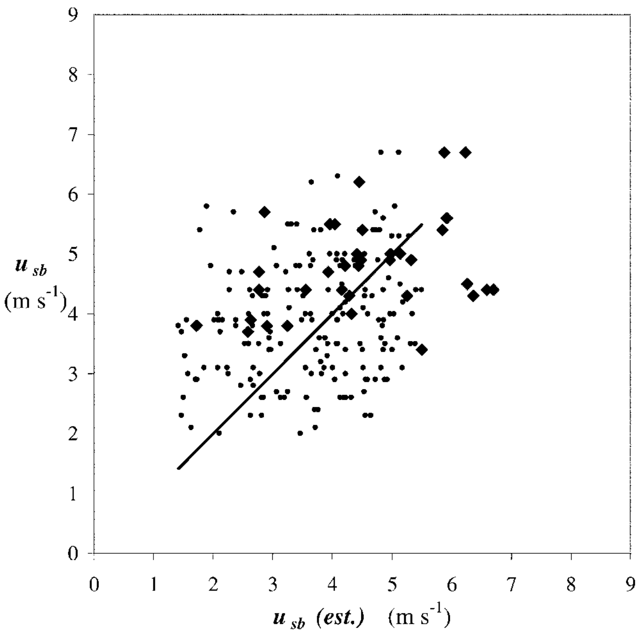


Figure 4. Scatterplot of the unscaled sea-breeze strength (u_{sb}) against the estimate for the sea-breeze strength (u_{sb} *(est.)*) obtained with the instantaneous sensible heat flux (relation 3). The dots represent all points prior to maximum sea-breeze strength and the diamonds represent the points at maximum sea-breeze strength.

antly to a value of 0.04. The value of coefficient α_3 is 2.42, which is almost equal to the value found in the figure with hidden correlation (e.g., 2.44). The standard deviation becomes 1.14 m s^{-1}. For the calculations with only the maximum sea-breeze strength, we find a value for coefficient α_3 of 2.95, which is only a little smaller than the value found with the hidden correlation (e.g., 3.11). The linear regression coefficient is small again, e.g., 0.12, and the standard deviation is 1.08 m s^{-1}, which is smaller than the standard deviation for the calculations with all hours prior to maximum sea-breeze strength. Thus the skill of relation (3) is rather disappointing.

Figure 5 shows the results with relation (4). The scatter in the plot (without hidden correlation) also appears to be larger than the scatter for relation (2) in Figure 3 (with the hidden correlation). This also turns out in the linear regression coefficients for the calculations with all hours prior to maximum sea-breeze strength as well as the calculations at maximum sea-breeze strength, 0.16 and 0.04 respectively. The values for coefficient α_4 are slightly smaller than the values obtained for relation 2, 0.66 (vs. 0.68 for relation (2)) on the basis of the calculations for all hours prior to maximum sea-breeze strength and 0.77 (vs. 0.80 for relation (2)) for calculations at maximum sea-breeze strength. The standard deviations are 0.85 for all calculations prior to maximum sea-breeze strength and 0.70 for calculations at

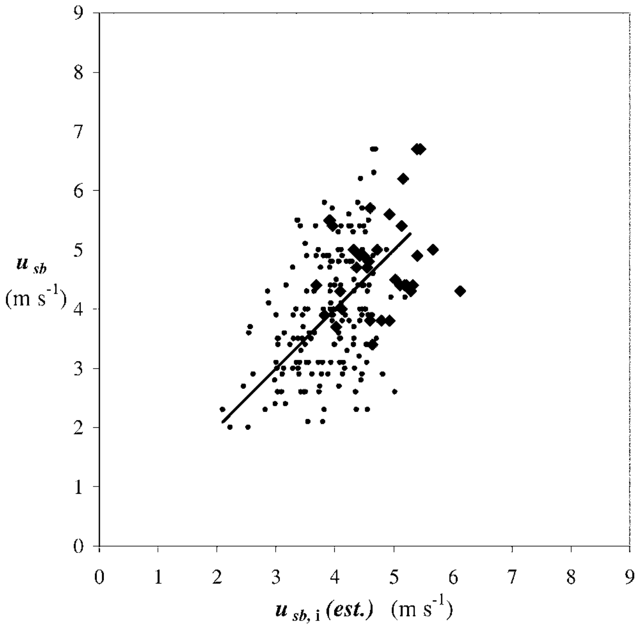


Figure 5. Scatterplot of the unscaled sea-breeze strength ($u_{sb,i}$) against the estimate for the sea-breeze strength ($u_{sb,i}$ *(est.)*) obtained with the time-integrated sensible heat flux (relation 4). The dots represent all points prior to maximum sea-breeze strength and the diamonds represent the points at maximum sea-breeze strength.

maximum sea-breeze strength. These standard deviations are significantly smaller than the standard deviations for relation (3) in Figure 4. This confirms that relation (4) gives better results than relation (3), although the correlation coefficients are low in both cases (due to small variations in the estimates). Nevertheless, the value of the coefficient α is rather robust for relations (1) and (3), and for relations (2) and (4).

The numerical results are summarized in Table I.

5. Discussion

From the results presented in Section 4 we can infer that for similar forcing, the maximum strength for the sea breeze in The Netherlands is about twice that in the Vancouver area of Canada. This can be explained as follows. First, note that the 10-m wind speed is not too different form the typical boundary-layer wind speed in the very unstable conditions examined. An increase of about 20% over a height of 200 m is typically obtained in such unstable conditions (see Holtslag, 1984) to which the calculations at maximum sea-breeze strength (around 1300 UTC) satisfy. Subsequently, according to Figure 6 from Steyn (1998), the average wind speed in the sea-breeze layer is about 0.7 times the maximum wind speed in the

TABLE I

Numerical results for station 210. The upper value is the value obtained from all points prior to maximum sea-breeze strength, while the lower value (between brackets) is the value obtained from only the points at maximum sea-breeze strength.

		α	r^2	σ
With corresponding terms on the x- and y-axes	Relation (1) – Figure 2	2.44	0.53	0.16
		(3.11)	(0.73)	(0.17)
	Relation (2) – Figure 3	0.68	0.78	0.09
		(0.80)	(0.88)	(0.10)
Without corresponding terms on the x- and y-axes	Relation (3) – Figure 4	2.42	0.04	1.14
		(2.95)	(0.12)	(1.08)
	Relation (4) – Figure 5	0.66	0.16	0.85
		(0.77)	(0.04)	(0.70)

previous SB max. strength

during max SB strength

sea-breeze layer. To compare the values of coefficients α_1 (3.11) and α_2 (0.80) from this study at maximum sea-breeze strength with the coefficients α_1 (1.10) and α_2 (0.31) from Steyn (1998 and 2003), our values of α should be multiplied by 1.2 (to convert to maximum wind speed in the sea-breeze layer) and 0.7 (to convert to average wind speed in the sea-breeze layer). In that case α_1 becomes about 2.61, which is more than twice the value for coefficient α_1 found by Steyn (1998). The value for coefficient α_2 then becomes about 0.67, which also is more than twice the value for coefficient α_2 found by Steyn (2003). Thus we find in either case that the values of the coefficients are about a factor 2 larger than the values found for the corresponding relations in Steyn (1998, 2003). This means that the sea breeze in The Netherlands is about twice as strong as in Vancouver. There are probably three effects that contribute to the difference found here: (i) The peninsula across Vancouver Bay will also develop a mesoscale breeze that counteracts the Vancouver City sea breeze. This will weaken the latter compared to the rather 'undisturbed' Dutch sea breeze. Moreover, the opposing sea breeze together with the Vancouver City sea breeze may cause stronger subsidence and stronger warming of the air over the bay. This will lead to a decrease in the surface pressure and surface pressure gradient driving the sea breeze. (ii) The surface sensible heat flux in the Vancouver experiments may not be representative of the average sensible heat flux due to influence of rivers and lakes with a lower heat flux. (iii) The surface sensible heat flux is affected by the sea breeze itself. The advection of cool sea air may increase the surface heat flux and this effect is dependent on the distance to the coast. Therefore the heat flux in the sea-breeze area is not representative for the average flux driving the sea breeze. Further inland this effect is smaller because the air has already been adjusted by the strong surface fluxes closer to the coast. Thus for testing the sea-breeze scaling relations, it is recommended to utilize heat flux observations outside the sea-breeze affected area. The latter appears to be the case in the current study, while in the studies for Vancouver the heat flux apparently was observed in the sea-breeze affected area.

6. Conclusions

In this study we show that some of the sea-breeze scaling relations in the literature incorporate hidden correlations. The impact of these hidden correlations on the value of the coefficient α (Equations (1)–(4)) is small, but the impact on the correlation is large. Moreover, we find that the relation with the time-integrated sensible heat flux gives better results than the relation that includes the instantaneous sensible heat flux.

Furthermore, the analysis of data shows that the sea breeze in The Netherlands is about twice as strong as the sea breeze in the Vancouver area in Canada. There are several effects that can explain the weaker sea breeze in Vancouver. To exclude one of these effects, we recommend that the sea breeze is scaled by a sensible heat flux that is representative of the average flux in the area of interest, and which is not influenced by the sea breeze itself. However, the current study shows that environmental effects may be larger (a factor of two in sea-breeze strength between The Netherlands and Vancouver, Canada) than the effect of latitude. Therefore the proposal by Steyn (1998, 2003) to include a latitude-dependency is overruled by other effects.

Overall, we find that relation (4) gives the best performance for our data with α_4 is 0.77. This suggests that on the basis of a time-integrated surface sensible heat flux estimate over land, a prediction can be made for the sea-breeze strength at 10 m height in calm synoptic conditions in rather homogeneous terrain. Further work may explore the practical usefulness of this in forecasting. Nevertheless, Tijm et al. (1999b) show the usefulness of scaling for the inland penetration of sea breezes.

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