On the Bowen Ratio and Surface Temperature at Sea[1]

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ABSTRACT

Gradients of temperature and humidity above water surfaces are analyzed in order to determine the dependence of the long-term average Bowen ratio β (the ratio of sensible to latent heat flux) on surface temperature. The least-squares fit that results from investigation of six such bodies of data, and which is supported by recent direct measurements of the fluxes by eddy correlation techniques, can be expressed as $\beta=0.63\ \gamma/s-0.15$, where γ is the ratio of the specific heat of air at constant pressure to the latent heat of vaporization of water and s is the slope of the saturated specific humidity curve at the surface temperature. This expression forms the basis of a model which can be used to determine the average surface temperature from routine observations of air temperature and humidity at sea.

1. Introduction

Evaluation of the air-sea interchange of heat, moisture and momentum is a matter of considerable interest to numerical modelers concerned with global-scale problems. Methods in common use for determining the surface sensible heat flux H and latent heat flux $\mathcal{L}E$ rely upon measurements of surface temperature T_s, although it is well recognized that routine observations of the surface temperature made from ships may be considerably in error since the surface itself is cooled by evaporation. In light winds the error involved may be as much as 1°C; this is often of the same order as the apparent surface to air temperature difference, from which estimates of H are derived. However, in these same conditions the values of H and $\mathcal{L}E$ may still be large because of the increased turbulent transfer due to buoyancy.

Surface temperature errors also enter analyses in another, more subtle manner. In most cases, the bulk transfer coefficients that are selected for application in some specific circumstance are derived from fluxes and surface to air temperature differences measured elsewhere. Consequently, any errors in the determination of surface temperature at the time of the field study will be reflected in the values quoted for the bulk transfer coefficients and may thus influence the interpretation of other data. These errors, however, may tend to be somewhat self-cancelling, provided that "erroneous" evaluations of bulk transfer coefficients are applied to similarly "erroneous" bulk data. The effect of surface temperature errors (usually T_s is too high) on evaluations of the bulk transfer coefficients is a direct reduction in the apparent magnitude of the coefficient D_H for sensible heat transfer and a somewhat smaller reduction in D_W for latent heat flux. Bearing in mind the apparent agreement between D_H and D_W reported by Pond *et al.* (1974), Dunckel *et al.* (1974), Smith (1974) and Hicks (1975), it seems possible that some of the seemingly anomalous results (i.e., $D_H \neq D_W$) that have been reported in the literature may have been an effect of surface temperature error.

The cool skin at the surface of the ocean has been the subject of a number of studies (e.g., Ball, 1954; Saunders, 1967; McAlister and McLeish, 1969; Hasse, 1971; Paulson and Parker, 1972; Khundzhua and Andreyev, 1974; Liu and Businger, 1975). The present aim is to devise a method by which investigators can check the quality of surface temperature observations using the more reliable measurements that are normally made of air temperature and humidity. In particular, we shall look for a relationship between the Bowen ratio $\beta\equiv H/\mathcal{L}E$ and the surface temperature-related property γ/s [where $\gamma\equiv c_p/\mathcal{L}$ is the ratio of the specific heat of air at constant pressure c_p to the latent heat of vaporization of water $\mathcal{L}$, and $s\equiv(\partial q_s/\partial T)_{T=T_s}$ is the slope of the saturated specific humidity curve at surface temperature T_s].

2. The dependence of β on T_s

A simple argument presented by Priestley (1959) suggests that over saturated surfaces we might find

$$\beta(T_s)=\gamma/s. \tag{1}$$

Relationships presented by Penman (1948) implied a similar dependence, and indeed such a concept is now

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TABLE 1. Sources of data used in the present analysis.

Author(s)	Comments
Large quantities of data over extended periods	
A. Takahashi (1958)	0.25–4 m gradients, Kagoshima Bay, Japan, 1953–1956.
B. Paulson (1967)	1.5–8 m gradients, constrained to good fetches, Indian Ocean, 1964.
C. Hoeber (1969)	H and $\mathcal{L}E$ inferred from gradients, equator, 30°W, 1965.
D. Paulson *et al.* (1972)	H and $\mathcal{L}E$ inferred from gradients, BOMEX, 1969.
E. Wieringa (1973)	2–4 m gradients, Lake Flevo, Netherlands, 1967.
F. Garratt (1974) Sahashi (1974)	Eddy fluxes in good fetches reported by Garratt, corresponding values of T_s given by Sahashi, AMTEX, 1974.
G. Krügermeyer (1975)	H and $\mathcal{L}E$ inferred from gradients, ATEX, 1969.
Limited quantities of data over short periods	
H. Rykatschew (1914)	1.5–6 m gradients, North Atlantic, 1913.
I. Wüst (1937)	0.2–2 m gradients from a buoy, North Atlantic, 1919.
J. Sverdrup (1946)	6–28 m gradients, North Pacific, 1937.
K. Gerhardt (1951)	1.5–13.7 m gradients, Gulf of Mexico, 1949.

relatively common in agricultural meteorology. However, a study by Priestley and Taylor (1972) indicated that Eq. (1) is considerably in error; their average result is

$$\mathcal{L}E/(R_n-G)=1.26s/(s+\gamma), \qquad (2)$$

where R_n is the net radiation and G is the heat transfer into the ground. When the energy balance relationship

$$H+\mathcal{L}E=R_n-G \qquad (3)$$

is substituted into (2), the result can be written as

$$\beta=0.79\gamma/s-0.21. \qquad (4)$$

Priestley and Taylor suggested that their result could be used in apportioning the turbulent heat loss to the atmosphere between H and $\mathcal{L}E$ over saturated surfaces. If this relationship were valid, then it would also be possible to eliminate surface temperature from the set of data necessary for the evaluation of heat fluxes from bulk aerodynamic measurements over a water surface, since β also can be written as

$$\beta=\gamma(\theta-T_s)/(q-q_s), \qquad (5)$$

where θ and q are potential temperature and specific humidity at 10 m height, and q_s is the saturated specific humidity at the temperature T_s. The analysis that follows is based on data sets that include either measurements of *in-air gradients* of both temperature and humidity or *direct determinations of the fluxes* by eddy correlation in order to eliminate surface temperature errors in evaluating β. Table 1 lists relevant observations in two groupings according to the quality and quantity of the material quoted.

It has been necessary to reject most of the older data because of both scatter and internal inconsistencies. As an objective criterion, the method used for discarding values that are apparently erroneous is based on the statistical distribution of each individual data set. After evaluation of the overall average Bowen ratio $\bar{\beta}$ and the corresponding standard deviation σ, all individual values falling outside the range bounded by $\bar{\beta}\pm2\sigma$ are eliminated. After recomputation, the rejection process is repeated until no further values are lost. Additional criteria for data selection are employed in some studies. An extended period of apparently anomalous strongly stable conditions reported by Hoeber (1969) is not included here. Some of the reported data of Takahashi (1958), Paulson (1967) and Garratt (1974) have been rejected because of the reported proximity to land and the corresponding poor fetch over the ocean. Other data of Takahashi (1958) have been rejected because the profiles were not monotonic.

Table 2 lists the average results derived from the analysis described above. The subset of seemingly better information has been used in constructing Fig. 1 which is a plot of β against γ/s. The dashed line shown in the diagram represents the behavior reported by Priestley and Taylor (1972). The solid line drawn in Fig. 1 is the least-squares regression line represented by

$$\beta=0.63\gamma/s-0.15. \qquad (6)$$

From Fig. 1 it appears that (6) is quite well determined, particularly at lower temperatures. In fairness, it

TABLE 2. Results derived from the data sources listed in Table 1.

Source code	Number of observations analyzed	Period of applicability of experiment	$\overline{T_s}$ (°C)	$\overline{\gamma/s}$	$\bar{\beta}$
A.	48*	3 years	24.9	0.369	0.071±0.040
B.	85	2 weeks	25.4	0.359	0.079±0.007
C.	240**	9 days	25.7	0.354	0.046±0.003
D.	141	11 days	28.2	0.312	0.042±0.001
E.	140	1 week	16.3	0.580	0.215±0.015
F.	142	10 days	19.4	0.491	0.160±0.008
	24	2 days	15.2	0.616	0.235±0.047
G.	18	18 days	27.0	0.332	0.074±0.005
H.	4	4 hours	16.2	0.583	0.264±0.005
I.	5	Uncertain	14.3	0.648	0.190±0.078
J.	4	Uncertain	21.2	0.446	0.121±0.038
K.	5	Uncertain	16.8	0.565	0.194±0.037

* A considerable amount of experimental scatter is evident; only monotonic profiles with good onshore fetch have been considered here.

** Omitting 66 observations made in strongly stable conditions.

should be pointed out that (6) results from an analysis in which two constants are determined, and hence a substantially better agreement with observations should be expected than in the case of the Priestley and Taylor formulation which allowed for only one empirical constant. It should be emphasized that intrinsically (6) should apply only to large time and space averages (e.g., seasonal and zonal). Furthermore, the available data do not allow a study to be made of the latitudinal dependence of the coefficients in (6), although there is indirect evidence in Fig. 1 that any such dependence is probably small.

It is possible that the Bowen ratio may exhibit some dependence on wind speed in addition to that on surface temperature described by (6). Table 3 presents the results of a correlation analysis performed in order to investigate this possibility, using data sets B, E and F. Although two of the regressions yield correlation coefficients that are statistically significant, the inferred dependencies are of opposite sign and hence the general wind speed dependence is uncertain. For the present, no effect of wind speed on the Bowen ratio will be considered.

3. Models for correcting the measured T_s

The relationship illustrated in Fig. 1 can be used to predict a sea surface temperature which should be compatible with observed air temperature, humidity and wind speed; this is done by simultaneously solving (5) and (6) for β and T_s. Thus, measured surface temperature can be eliminated from the necessary data base for use in bulk aerodynamic studies of oceanic heat exchange with the atmosphere.

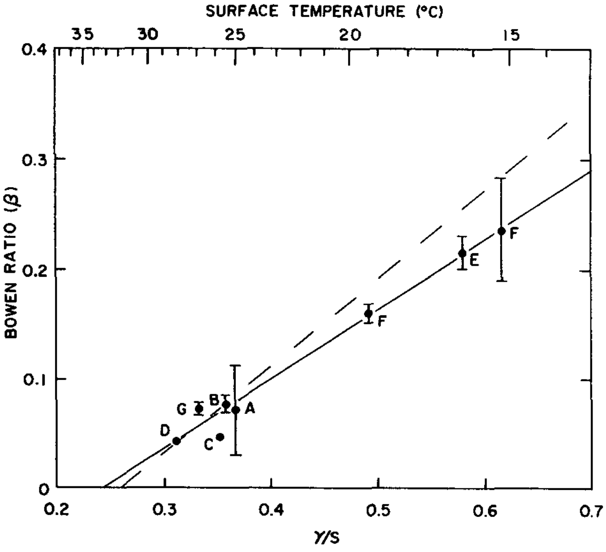

FIG. 1. The dependence of the Bowen ratio over water surfaces on the surface, temperature-related property γ/s. All evaluations of the Bowen ratio are based on in-air gradients or on direct eddy correlation measurements of the appropriate fluxes. The surface temperature is approximated by the measured surface temperature T_{ss}. Data used are identified in Table 1. Standard error bars are shown, except in those cases for which the standard error is too small for illustration. The solid line is the result of a linear regression analysis, and the dashed line represents the behavior reported by Priestley and Taylor (1972).

TABLE 3. Results of a correlation analysis between Bowen ratio and wind speed. $\bar{T}_s$ is the appropriate average surface temperature and m is the number of observations.

Data set	$\bar{T}_s$ (°C)	m	Correlation coefficient
B. (Paulson, 1967)	25.4	85	−0.19
E. (Wieringa, 1973)	16.3	140	0.45
F. (Garratt, 1974; Sahashi, 1974)	19.4	142	0.13
	15.2	24	−0.43

As mentioned in Section 1, alternative procedures also are available. By assuming a subsurface viscous boundary layer the temperature difference across the layer can be expressed as

$$T_{ss}-T_s=(\lambda Q\nu/\kappa)\cdot(\rho_a u_*{}^2/\rho_w)^{-\frac{1}{2}} \tag{7}$$

(following Saunders, 1967), where T_{ss} is the subsurface temperature, u_* is the friction velocity in the air, Q is the total subsurface heat flux ($Q=H+\mathfrak{L}E+R$, where R is the net efflux of longwave radiation), ν is the kinematic viscosity of water, κ is the thermal conductivity of water, ρ_a and ρ_w are the densities of air and water, respectively, and λ is a constant to be evaluated empirically. Saunders suggests $\lambda\approx 7$ and Paulson and Parker (1972) point out that this gives good agreement with the predictions of an alternative but similar model put forward by Hasse (1971), i.e.,

$$T_{ss}-T_s\approx C_1 Q/U, \tag{8}$$

where C_1 is a constant and U is the wind speed at 10 m height. The value of C_1 is found by Hasse to be 9.9 when T_{ss} measurements are made at 1 m depth, and heat fluxes are expressed in cal cm^{-2} min^{-1} and velocities in m s^{-1}. The value of C_1 varies slightly with the depth of measurement of T_{ss}; $C_1=9.4$ at 25 cm depth.

The two formulations for $(T_{ss}-T_s)$ given above may be incorporated in bulk aerodynamic relationships without difficulty, provided that net infrared radiation values are known so that the total heat flux Q can be evaluated. Several methods for evaluating the net infrared efflux are available [e.g., those given by Ångstrom (1916), Brunt (1932), Budyko (1963; 1974, pp. 57–62) and Swinbank (1963)]. However, the values of the clear-sky net infrared radiation obtained from these four relationships vary considerably, particularly in low latitudes where the range amounts to a factor of more than 2. Because there appears to be no clear experimental evidence favoring any one of these formulas, our results shall be based on the average of the four estimates. We wish to emphasize that this uncertainty in the estimate of the net infrared radiation,

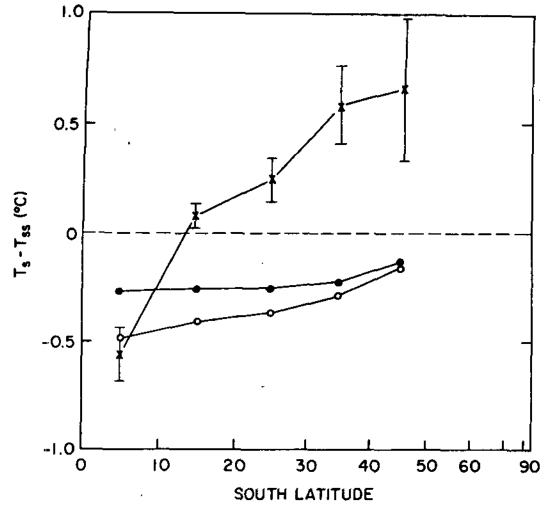

FIG. 2. Variation with latitude of the apparent temperature difference between the sea surface and subsurface water, according to the model of Saunders (●) and Hasse (○) and as given by the present arguments concerning Bowen ratios (×). Data are based on ship reports supplied to the Australian Bureau of Meteorology, between 1961 and 1966 (Hess and Hicks, 1976).

even in clear-sky conditions, means that the estimate of surface temperature errors by (7) or (8) for climatological data, such as in our case, should be viewed with caution.

A correction to these estimates must be made to account for the effects of cloud cover. We have used the formulation given by Budyko (1958) which relates the net infrared radiation component R to the value R_0 in clear sky conditions and the cloud cover n (in tenths),

$$R=R_0(1-cn^2), \qquad (9)$$

where c is a slowly changing function of latitude (about 0.5–0.8). This relationship, too, should not be taken to be securely determined. The data for cloud cover used in our estimates are derived from satellite observations (Clapp, 1964).

4. Comparison of models

A body of bulk aerodynamic data generated from ship reports collected by the Australian Bureau of Meteorology between 1961 and 1966 has been used to test the alternative methods of obtaining the true surface temperature. This body of data is described in detail by Hess and Hicks (1976). For the present purposes it is sufficient to point out that considerable care has been taken to delete erroneous values from the data set, and also that the influence of nearby land has been minimized by omitting all observations which were made in 10° longitude squares that include a significant land area. Values of H and $\mathcal{L}E$ have been obtained by applying the methods outlined by Hicks (1975), which are essentially similar to the use of constant bulk transfer coefficients equal to 0.00145 for both fluxes. The evaluations of H and $\mathcal{L}E$ are based on corrected surface temperatures obtained by iteration.

Fig. 2 shows the variation with latitude of the annual average difference between the measured "surface" temperature T_{ss} and the value T_s estimated from the application of (5) and (6). Also shown are the temperature differences given by the relationships proposed by Saunders (1967) and by Hasse (1971).

The apparent agreement at low latitudes between the present estimates of surface skin cooling and the predictions made using more conventional models generates some confidence in the quality of the data used. In this region near the equator under conditions of light winds, we might expect that the underlying assumptions of (7) and (8) would be best fulfilled. However, the Bowen ratio technique shows a substantially different behavior than the other models at latitudes greater than 10°S; in fact it predicts that the actual surface temperature is *warmer* than the subsurface temperature. For strong wind conditions we would expect increased mechanical mixing and thus a decrease in the temperature difference, but not a change in sign. Error bars based on the T_{ss} data are plotted in Fig. 2 and indicate that the result has some statistical significance. It is possible that this result is due to systematic errors in the data at higher latitudes; the reported "surface" temperatures (T_{ss}) may be consistently too low, *both* the dry- and wet-bulb temperatures may be consistently too high, or there may be a consistent error in (4) which is not apparent in the field experiments from which it was deduced. Another (but relatively unlikely) possibility is that the anomalous surface skin temperature differences at high latitudes are real. Insolation and other radiative effects associated with the complicated structure of the surface or turbulent energy dissipation from wave breaking could conceivably provide a source of heating at the surface which has not been detected. At present there are no measurements known to us which are reliable enough to test such hypotheses.

5. Conclusions

The work by Priestley and Taylor (1972) permits incorporation of sensible and latent heat fluxes based on large-scale parameters in models of the global general circulation of the atmosphere. In this regard, they were concerned with the behavior over land surfaces, and especially over crops or different water status. The present study, however, is restricted to the oceanic case where the theoretical arguments of the Bowen ratio model are best satisfied. The relationship illustrated in Fig. 1, which is based on experimental studies in a variety of circumstances, seems to be very well determined, although more experimental data over a wider range of temperatures would be desirable.

It is anticipated that the present description of the Bowen ratio over open water surfaces [i.e., (6)] may be applicable in a number of ways, provided the time scale is long compared to the synoptic time scale. It should be especially relevant to numerical models concerned with the average state of the sea and to the computation of oceanic fluxes. However, we wish to point out that the present analysis is limited to surface temperatures above about 16°C, and hence the latitudinal range of applicability is limited to about ±40°. A further cautionary note is that the surface temperatures inferred by the straight line relationship of Fig. 1 must still be regarded as tentative and do not agree with those predicted by the models of Saunders (1967) and Hasse (1971).

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REFERENCES

Ångstrom, A., 1916: Über die Gegenstrahlung der Atmosphäre. *Meteor. Z.*, **33**, 529–538.

Ball, F. K., 1954: Sea surface temperatures. *Aust. J. Phys.*, **7**, 649–652.

Brunt, D., 1932: Notes on radiation in the atmosphere. *Quart. J. Roy. Meteor. Soc.*, **58**, 389–420.

Budyko, M. I., 1958: The heat balance of the earth's surface. N. A. Stepanova, transl., Office of Tech. Serv., U. S. Dept. of Commerce, Washington, D. C., 259 pp.

——, 1963: *Atlas Teplovogo Balansa Zemnogo Shara.* Gidrometeorologichesko Izdatel'skoe, Moscow, 69 pp.

——, 1974: *Climate and Life.* Academic Press, New York, 508 pp.

Clapp, P. F., 1964: Global cloud cover for seasons using TIROS nephanalyses. *Mon. Wea. Rev.*, **92**, 492–507.

Dunckel, M., L. Hasse, L. Krugermeyer, D. Schriever and J. Wucknitz, 1974: Turbulent fluxes of momentum, heat and water vapor in the atmospheric surface layer at sea during ATEX. *Bound.-Layer Meteor.*, **6**, 81–106.

Garratt, J. R., 1974: Turbulent flux measurement by CSIRO. AMTEX '74 Data Rep., Vol. 4, 60–67.

Gerhardt, J. R., 1951: Temperature and moisture soundings over the Gulf of Mexico for March, 1949. *Trans. Amer. Geophys. Union*, **32**, 15–25.

Hasse, L., 1971: The sea surface temperature deviation and the heat flow at the sea-air interface. *Bound.-Layer Meteor.*, **1**, 368–379.

Hess, G. D., and Hicks, B. B., 1976: Climatological fluxes of momentum, heat, and moisture over the ocean. (To be submitted for publication to *J. Phys. Oceanogr.*)

Hicks, B. B., 1975: A procedure for the formulation of bulk transfer coefficients over water. *Bound.-Layer Meteor.*, **8**, 515–524.

Hoeber, H., 1969: Wind-, Temperature und Feuchteprofile in der wassernahen Luftschicht über dem äquatorialen Atlantik. *"Meteor" Forschungsergebnisse, Reihe B*, No. 3, 1–26.

Khundzhua, G. G., and Ye. G. Andreyev, 1974: An experimental study of heat exchange between the ocean and the atmosphere in small-scale interaction. *Atmos. Ocean. Phys.*, **10**, 1110–1113.

Krügermeyer, L., 1975: Vertikale Transporte von Impuls, sensibler und latenter Wärme aus Profilmessungen über dem tropischen Atlantik während APEX. Berichte Inst. Radiometeor. Maritime Meteor., No. 29, 102 pp.

Liu, W. T., and J. A. Businger, 1975: Temperature profile in the molecular sublayer near the interface of a fluid in turbulent motion. *Geophys. Res. Lett.*, **2**, 403–404.

McAlister, E. D., and W. McLeish, 1969: Heat transfer in the top millimeter of the ocean. *J. Geophys. Res.*, **74**, 3408–3414.

Paulson, C. A., 1967: Profiles of wind speed, temperature and humidity over the sea. Dept. Atmos. Sci., University of Washington, Sci. Rept. NSF GP-2418, 128 pp.

——, and Parker, T. W., 1972: Cooling of a water surface by evaporation, radiation, and heat transfer. *J. Geophys. Res.*, **77**, 491–495.

——, E. Leavitt and R. G. Fleagle, 1972: Air-sea transfer of momentum, heat and water determined from profile measurements during BOMEX. *J. Phys. Oceangr.*, **2**, 487–497.

Penman, H. L., 1948: Natural evaporation from open water, bare soil and grass. *Proc. Roy. Soc. London*, **A193**, 120–145.

Pond, S., D. B. Fissel and C. A. Paulson, 1974: A note on bulk aerodynamic coefficients for sensible heat and moisture fluxes. *Bound.-Layer Meteor.*, **6**, 333–340.

Priestley, C. H. B., 1959: *Turbulent Transfer in the Lower Atmosphere.* The University of Chicago Press, 130 pp.

——, and R. J. Taylor, 1972: On the assessment of surface heat flux and evaporation using large-scale parameters. *Mon. Wea. Rev.*, **100**, 81–92.

Rykatschew, M. M., 1914: Meteorologische Beobachtungen und Beobactungen in den verschiedenen Schicten der Atmosphäre, die aut dem schwimmenden Leuchtturme Lüserort angestellt worden sind. *Meteor. Z.*, **31**, 328–339.

Sahashi, K., 1974: Measurement of mean profile and flux on Tarama off-shore tower. AMTEX '74 Data Report, No. 4, 75–87.

Saunders, P. M., 1967: The temperature at the ocean-air interface. *J. Atmos. Sci.*, **24**, 269–273.

Smith, S. D., 1974: Eddy Flux Measurements over Lake Ontario. *Bound.-Layer Meteor.*, **6**, 235–256.

Sverdrup, H. U., 1946: The humidity gradient over the sea surface. *J. Meteor.*, **3**, 1–8.

Swinbank, W. C., 1963: Long-wave radiation from clear skies. *Quart. J. Roy. Meteor. Soc.*, **89**, 339–348.

Takahashi, T., 1958: Micro-meteorological observations and studies over the sea. Rep. No. 6, Dept. Aquatic Sciences, Kagoshima University, Japan, 1–46.

Wieringa, J., 1973: Applications of turbulence measurements over Lake Flevo. D. Sc. dissertation, University of Utrecht, The Netherlands, 96 pp.

Wüst, G., 1937: Temperatur- und Dampfdruckgefälle in den untersten Metern über der Meeresoberfläche. *Meteor. Z.*, **54**, 4–9.