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Theoretical
and Applied
Climatology

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Estimating the annual mean screen temperature empirically

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With 9 Figures

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Summary

We have examined station data from around the world to study the separate effects of the latitude (between 60° N–40° S), elevation and distance inland, on the annual-mean screen temperature. In the first 200–400 km from some west coasts, screen temperatures (after adjustment for elevation) rise inland, reaching a maximum called the 'thermal-ridge temperature' Tr. The rise of temperature within this littoral fringe (of width F) depends mainly on the difference between the sea-surface temperature off the west coast and the zonal mean. Further inland than such a fringe, adjusted temperatures generally decline eastwards, approximately linearly, at a rate C. The rate is related to hemisphere and latitude.

Empirical relationships between latitude and the observed coastal sea-surface temperature, the near-shore screen temperature, Tr, C and F for each continent are used to estimate annual mean temperatures on land. Independent estimates of this kind for 48 places, using a look-up table, differ overall by only 0.7 K from the actual long-term average annual mean temperatures. This is less than half the error resulting from an assumption of zonal-mean temperatures. Basing estimates on coastal sea-surface temperatures, instead of the look-up table, results in an average error of 1.0 K for the 48 places. The errors are comparable with the standard deviation of annual mean temperatures during 30 years or so.

1. Introduction

There are several reasons for estimating features of the climate of a place by assuming the relevance of available measurements from geographically similar locations. Firstly, no measurements may have been made at the place in question. Secondly, measurements can be compared with an estimate, as a check on any eccentricity of the observations, provided we know that the estimate is commonly of useful accuracy. Significant difference between estimate and measurement signals some regional or local peculiarity, which may warrant investigation. Errors in estimating based on only three geographic factors (viz. latitude, elevation and distance from the sea) indicate the degree to which more local factors govern the climate. Thirdly, being able to deduce climate from geographic features implies the reverse, an ability to identify places with known climates, e.g. homoclimes. Lastly, and importantly in teaching climatology, quantitative empirical associations of numerical values of climate elements (with each other and with geographic factors) provide clues to the relative magnitudes of the mechanisms responsible, and represent an advance on the merely qualitative generalisations customary in textbooks.

The question to be answered is this – how accurately can we estimate the annual mean temperature at screen level at a locality on land, from our present knowledge of the effects of large-scale geographical features? This is not answered properly by available multiple-regression studies, involving merely statistical interpolation between observations, e.g. Zheng and Basher (1996). That approach ignores physical processes involving the distance from the sea and the sea breezes, for example. Instead, we will attempt to disentangle the large-scale factors affecting annual mean temperatures generally. We consider only latitudes between 40° S–60° N, where most people live and temperatures are little affected by the high albedo and latent heat of ice.

We begin by considering the effect of elevation on annual mean temperatures, in order to 'adjust' observed temperatures to their sea-level equivalents, thus allowing a common basis for comparisons. The second variable to be considered is the latitude, to permit 'correcting' observations from places of similar latitude to the equivalents at a selected common latitude nearby. On removal of the dominant effects of elevation and latitude, we can examine the effect of eastward distance from the ocean. Then we can use the information to estimate the temperature at each of numerous selected places, for comparison with the observed values.

Much of the evidence comes from the book by Linacre and Geerts (1997), hereafter referred to as LG97, secondly from Linacre (1992), i.e. L92, and thirdly from Linacre and Hobbs (1977), i.e. LH77. Some climate data come from Pearce and Smith (1990), based on 'Tables of Temperature, Relative Humidity and Precipitation of the World' (Met. 617, Her Majesty's Stationery Office, London, 1958 et seq.). However, most of the climate-station data used here have been extracted from the International Station Meteorological Climate Summary v 4.0 (1996), available on a CD-ROM from the US National Climate Data Center (www.ncdc.noaa.gov). Also, we make considerable use of the NCAR/NCEP global reanalysis data set (at a resolution of 2.5 degrees), which is based on weather station, buoy, ship, upper-air and satellite data (Kalnay et al., 1996). These data were mined on-line at the web-site of the US Climate Diagnostics Center, http://www.cdc.noaa.gov) using monthly-mean values for the period 1968–1996.

2. The effect of elevation on the annual mean temperature

Average temperatures fall with elevation, both in the free atmosphere and on rising ground. The International Civil Aviation Organization's Standard Atmosphere lapse rate is 6.5 K/km in free air in the troposphere. (Note that temperature *differences* are here expressed in units Kelvin, whereas temperatures themselves are in Celsius units.) But lapse rates of screen temperatures in mountainous terrain are affected by heat transferred to and from the ground surface, and by topographically induced winds. The air near the ground is generally warmer than free air at the same level, in warm latitudes and seasons.

Various ground-level lapse rates have been reported in the literature. Data from 34 places between 0–34° S in Africa (LG97, p. 370) lead to a relationship between the annual mean temperature (here taken as the average of observed January and July mean temperatures), the latitude and the elevation, implying a lapse rate of 3.8 K/km. Temperatures from places in South America show a ground-level lapse rates of about 4.2 K/km (LG97, p. 58), 4.9 K/km (LG97, p. 68) and 5.0–6.1 K/km (Safford, 1999). In addition, we have found that lapse rates at a spacing of 5-degrees latitude on the east of the Andes range from 3.4–7.6 K/km, with an average of 5.3 K/km. (Rates on the *west* of the Andes are scattered around only 2.9 K/km, but that is explained by mid-level inversions due to cold coastal seas – see Note 11.E in LG97.) Likewise, data from 18 places on the east of the Himalayas (between 28–33 degrees of latitude and 93–104 longitude) indicate an overall value of 5.0 K/km.

These various lapse rates have a median of 5 K/km and that figure will be used in what follows. Applying it to a value of ground-level temperature at a given height provides the sea-level equivalent, which we call the 'adjusted' temperature. Adjusted temperatures allow comparison of conditions independently of elevation.

Fortunately, the choice of the lapse-rate value is not critical in estimating the annual mean temperature at a place, because of the procedure adopted. This involves initial 'adjustment' of observed values, to derive relationships with temperatures at sea level, and hence an estimate of the adjusted temperature for a particular place. This is subsequently adjusted using the same lapse rate, but *in reverse*, to obtain the estimate of the actual temperature at the height of that place. In other words, there is some cancellation of the effect of the lapse rate.

3. The effect of latitude on the annual mean temperature

3.1 Land and sea together

The latitude obviously affects temperatures, and, excluding the highest latitudes, the relationship is approximately quadratic, as reported previously (L92, p. 72). The quadratic decrease of temperature with latitude is due to the combination of two effects of the Sun's angle – i) the obliquity of the Sun's rays, and ii) the consequent increase of path length through the atmosphere. Figure 1 shows that zonal mean adjusted temperatures (Tm: °C) over ocean and land between 70° S–70° N fit the following formulae, where L is the latitude in degrees:

$$\text{north hemisphere:} \quad Tm = 27.8 - 0.0076\,L^2 \tag{1a}$$

$$\text{south hemisphere:} \quad Tm = 26.5 - 0.0078\,L^2 \tag{1b}$$

The fact that Eq. (1a) and (1b) are not identical reflects the contrast between the globe's hemispheres. Firstly, the South Pole is far colder than the North Pole, because of the extent and elevation of Antarctica, and its isolation from lower-latitude warmth by the vortex of polar winds. Secondly, there is asymmetry between the land masses in the respective hemispheres, resulting in the latitude of highest temperature being at about 10° N over land (Geer, 1996; p. 109) and 15° N globally. There is only half as much land in the southern hemisphere as in the northern, and the Earth's continents taper towards the equator in the northern hemisphere, but towards the pole in the southern. The asymmetry is confirmed indirectly by average summertime heights of the snowline; the latitude at which it is 3 km high is 35° S in the south but about 45° N in the north (LG97, p. 58). Also, the latitude of least annual range of the monthly mean extra-terrestrial radiation is 4° N (Linacre, 1969, p. 4). The northward bias should to be borne in mind in some of what follows. In other parts, we simplify by treating the hemispheres as mirror images of each other.

Differentiation of Eq. (1) shows a meridional gradient of temperature of about 0.016 L degrees Kelvin per degree of latitude. Thus an observation at a latitude [L–ΔL] degrees can be 'corrected' to a value at latitude L degrees, by subtracting 0.016 ΔL.L Kelvin. (For instance, a value of 20 °C at 28 degrees of latitude is equivalent to 19.0 °C (i.e. $20 - 0.016 \times 2 \times 30$) at 30 degrees. This allows measurements near a chosen latitude to be brought to a common basis.

Henceforth, unless stated otherwise, we shall use only data which have been brought to a specified latitude by 'correction' and to zero elevation by 'adjustment'. As a result, we can explore the effects of other factors controlling mean temperatures, notably the distance inland from the sea.

3.2 Temperatures of the sea surface at the edges of the oceans, Ts

Annual-mean coastal sea-surface temperatures (SST), Ts, estimated as the mean of the August and February values, are summarised in Table 1. It can be seen that waters along east coasts at

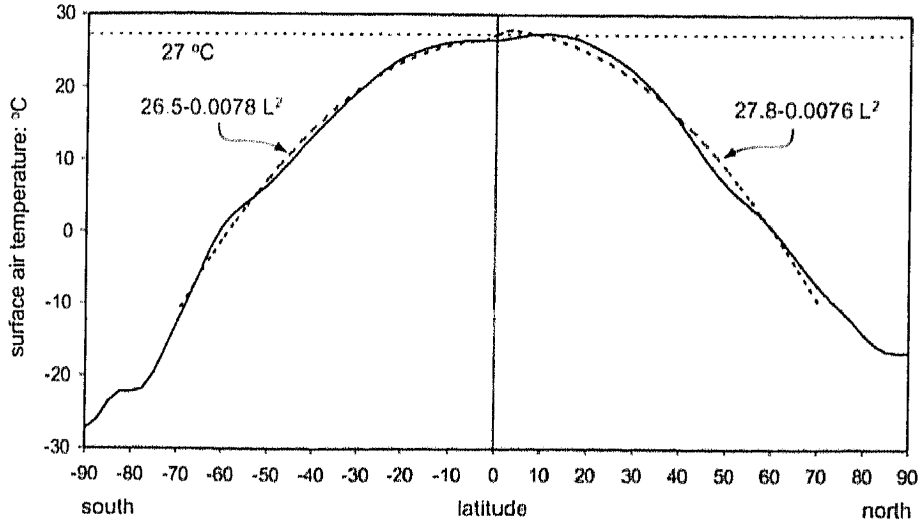

Fig. 1. The variation with latitude of the zonal, longterm-mean sea-level 'adjusted' screen temperature (solid line), based on the NCAR/NCEP global re-analysis. The dashed lines represent a quadratic relationship fitted for each separate hemisphere

Table 1. Annual mean coastal sea-surface temperatures Ts (°C) on the western and eastern edges of the Pacific, Atlantic and Indian oceans. (Sverdrup et al., 1946; LG97, p. 221; NCAR/NCEP global re-analysis data-set; Reynolds and Smith, 1995; Smith and Reynolds, 1998.)

Latitude: degrees	Continent	Tsw, west coast	Continent	Tse, east coast
60	**North America**	8	**North America**	3
50		11		5
40		13		13
30		17		25
20		26		27
10	**South America**	27	**South America**	27
0		23		27
−10		19		26
−20		17		25
−30		17		21
−40		13		13
60	**Europe**	11	**Asia**	3
50		13		6
40		17		13
30	**Africa**	19		21
20		21	**Africa**	26
10		26		27
0		26		26
−10		23		26
−20		17		26
−30		16		22
20	**India**	27	**India**	27
10		28		28
20		27		25
10	**S.E. Asia**	27	**Philippines**	28
0	**Indonesia**	28	**Papua**	28
−10	**Australia**	27	**Australia**	27
−20		26		24
−30		20		21
−40		14		14

low latitudes tend to be warmer than those on west coasts. This is also evident in Fig. 2, which shows departures from zonal mean temperatures Tm (Eq. 1). The difference between waters on the two coasts of a continent is caused partly by warm boundary currents flowing from the equator along east coasts up to about 40° latitude. Conversely, local upwelling and currents from the poles cool the west coasts of Africa and the Americas at low latitudes.

3.3 *The coastal temperature, Tc*

Temperatures from land-based weather stations near the shoreline are here labelled Tc and plotted in Fig. 3. About two-thirds of the values are from places within 3 km of the sea, and all are within 12 km. Onshore coastal temperatures Tc in Fig. 3 are highest around 10° N, in accord with the asymmetry about the equator noted in Section 3.1.

Comparison of the two parts of Fig. 3 shows considerable differences between the values of Tc on west and east coasts. East coasts are colder than those on the west, north of 40° N (Fig. 3). This is opposite to the comparison of coastal water temperatures Ts: *west* coastal waters are the cooler (Section 3.2). The consequence is that the sea is warmer than the shore on east coasts (especially at high northern latitudes), but contrariwise on most west coasts. Correlation of Ts and Tc values at places along the various coasts yields the following relationships:

$$\text{west coasts:}\quad Tcw = 1.11\,Tsw - 2.1 \qquad (2a)$$

$$\text{east coasts:}\quad Tce = 1.23\,Tse - 5.9 \qquad (2b)$$

where the suffix 'cw' in Eq. (2a) implies coastal onshore measurements on *west* coasts, whilst 'se' in Eq. (2b) identifies the SST on *east* coasts, for example. The correlation coefficients of the relationships are 0.95 for Eq. (2a) and 0.92 for east coasts.

The variation of Tc with latitude is far greater than any longitudinal variation of Tc along east-west oriented coasts. For instance, corrected shoreline temperatures east of Fisherman's Lake at 7° N in West Africa, of Tangiers at 35° N on the Mediterranean coast of Africa, and of Cape Leeuwin at 35° S in southern Australia all show constancy within about 1 K over 1900–3400 km, i.e. along the entire coast facing either south or north.

3.4 *The littoral fringe*

Temperatures inland vary with distance from the shore, according to whether it is a west or east coast. Let us first consider west coasts. A score of zonal transects of adjusted temperatures from west coasts show the same pattern as in Fig. 4. There is initially a rise (the 'littoral warming') from the shoreline temperature Tc, reaching a maximum (the 'ridge temperature' Tr) at the peak of what will be called a 'thermal ridge'. Thereafter, there is a steady eastward fall of

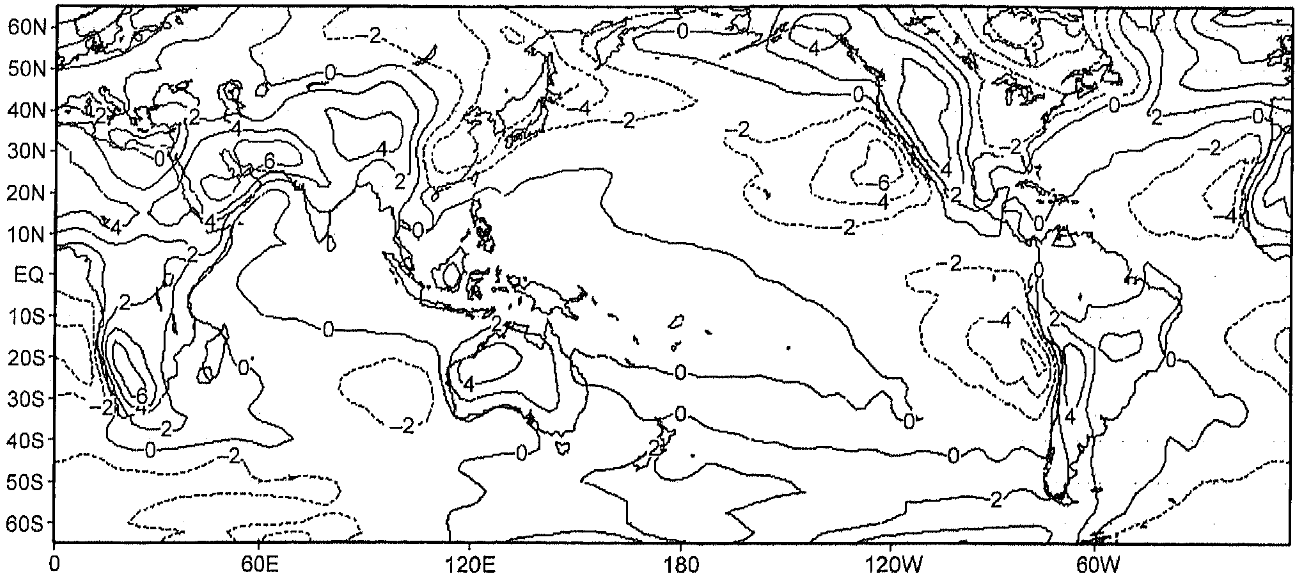

Fig. 2. Departures of adjusted temperatures from the zonal means Tm (Fig. 1), based on the NCAR/NCEP global re-analysis

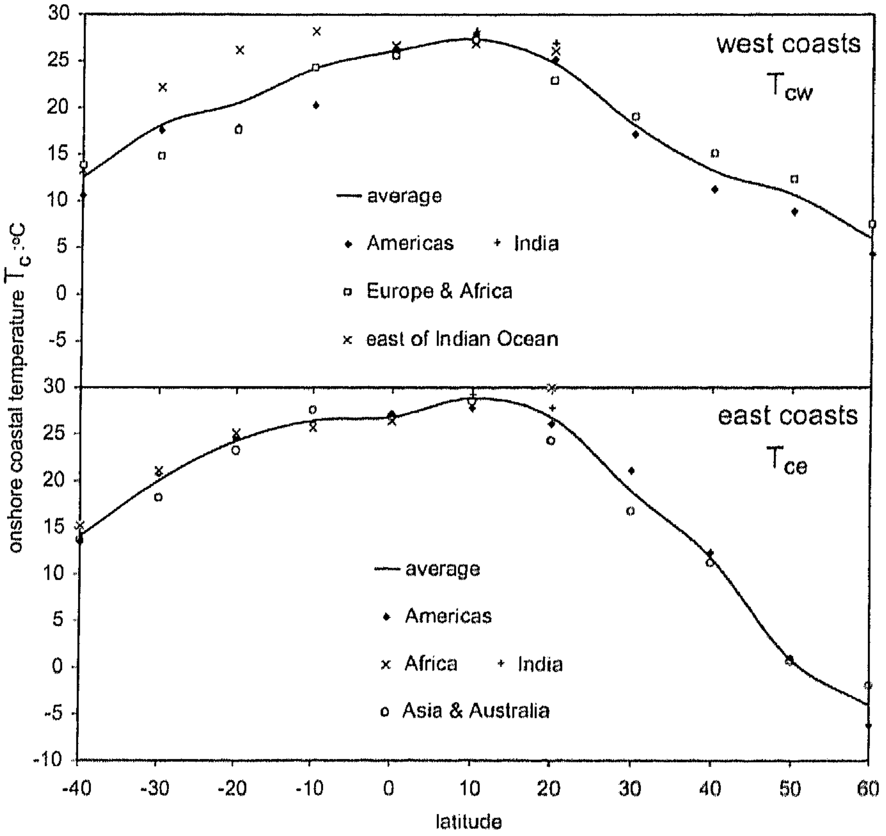

Fig. 3. The variation with latitude of near-shoreline weather-station annual-mean screen temperatures Tc, showing data from various continents. Negative latitudes are in the southern hemisphere

annual-mean adjusted temperature. The coastal strip containing the littoral warming is here called the 'fringe'. Its characteristic is a positive temperature gradient away from the shore, about an order of magnitude steeper than a negative gradient on the far side of the ridge (Section 4).

In the Americas, for instance, a topographic ridge is present near the west coast, in the vicinity

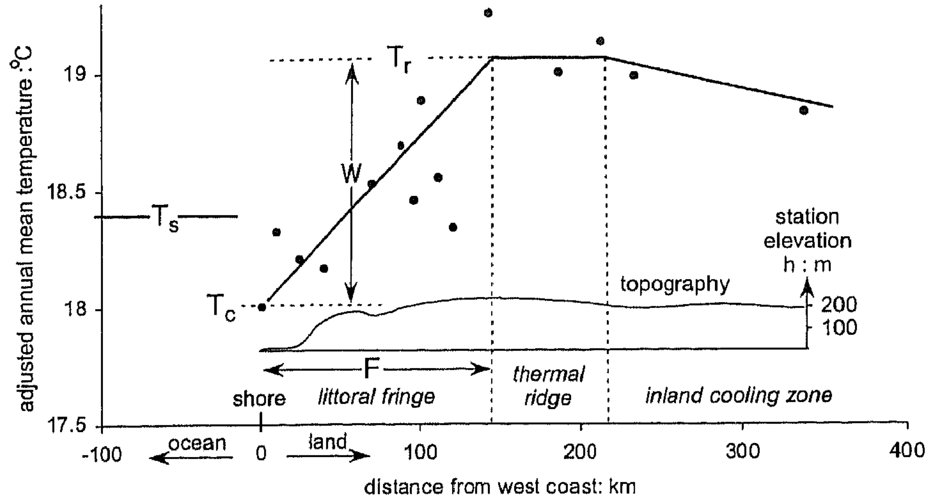

Fig. 4. The variation eastwards from the west coast of Australia of adjusted annual mean temperatures corrected to 32° S. This shows i) Ts (the SST at the ocean's edge, Table 1), ii) the 'coastal temperature' Tc, i.e. the screen temperature near the shoreline (Section 3.3), iii) the 'thermal ridge', the place of maximum adjusted temperature Tr (Sections 3.4 & 3.5), and the littoral warming, shown here as W. The diagram also includes a profile of the elevations of the recording stations, as proxy for the topography along the transect

of the thermal ridge. So it might be argued that the thermal ridge is an artifact of the temperature adjustment to sea level. However, transects like that in Fig. 4, but across Chile at 20° S and across Canada at 50° N, show that adjusting by means of a lapse rate of only 3.0 K/km instead of 5.0 K/km may extend the apparent width of the fringe, but the change of lapse rate makes little difference to the inferred littoral warming. In the Chilean case, the fringe width is increased from about 500 km to 800 km, but in the Canadian case it remains at about 350 km. The warming across the fringe in Chile is reduced from 10.3 K to 8.3 K and in Canada from 1.6 K to 1.3 K. However, in neither case does a different lapse rate alter the fact of a fringe and the reality of a thermal ridge. Also, it will be shown in Section 3.6 that there are places where a fringe exists even without high mountains near the coast, where consequently lapse rates are irrelevant.

There are no similar fringes (with thermal ridges) on east coasts, because there the sea is warmer than the land, in terms of annual mean temperatures (Section 3.3).

3.5 The ridge temperature, Tr

The temperatures of west-coast thermal ridges have been determined from transects of adjusted and corrected temperatures from 22 places on

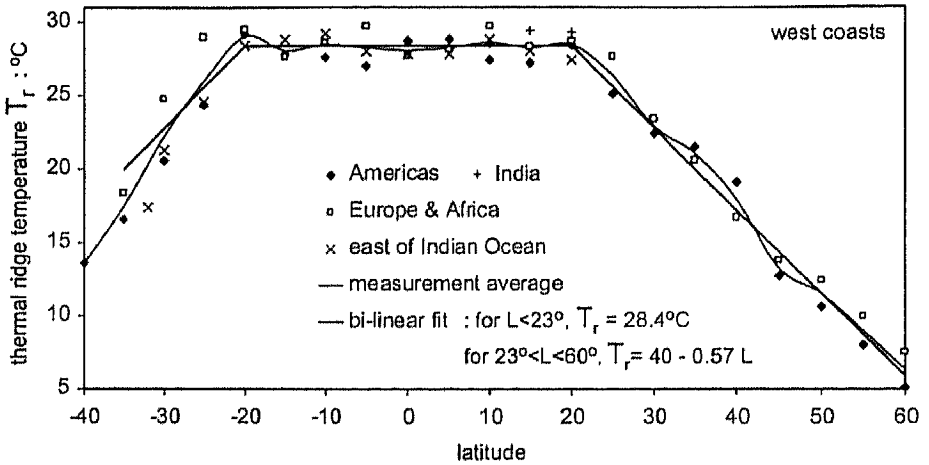

Fig. 5. The variation with latitude of the ridge temperature Tr

Table 2. Features of 22 transects similar to that in Fig. 4. All of these show a thermal ridge and a littoral warming rate of at least 1 K within about 100 km of the west coast. L is the latitude (degrees). R is the distance eastward from the west coast to land at 1,000 m elevation; a blank means no such mountain within the fringe. Values of the zonal mean temperature Tm came from Eq. 1, and coastal-water temperatures on west coasts Tsw from Table 1. The term [Tsw−Tm] represents the SST anomaly. Tcw is the observed annual mean temperature onshore at the west coast. F is the approximate fringe width, i.e. the distance of the western edge of the thermal ridge from the west coast (Fig. 4). Tr is the temperature at that ridge, and [Tr−Tcw] is the 'littoral warming'

Continent	Place	L: °lat	R: km	Tm: °C	Tsw: °C	Tsw−Tm: K	Tcw: °C	F: km	Tr: °C	Tr−Tcw: K
North America	Port Alice	50	230	8.8	8.6	−0.2	7.5	350	9.1	1.6
	Newport	45	170	12.4	10.7	−1.7	10.7	300	12.7	2.0
	San Francisco	37	260	17.4	14.2	−3.2	14.4	500	21.8	7.4
	Los Angeles	34	100	19.0	14.6	−4.4	16.2	470	23.9	7.7
	Ensenada	31	350	20.5	17.0	−3.5	17.4	400	22.9	5.5
South America	Mazatlan	23	250	23.8	21.8	−2	21.2	250	24.9	3.7
	Puerto Vallarta	21	60	24.4	23.6	−0.8	22.9	200	26.2	3.3
	Mollendo	−17	100	24.2	16.6	−7.6	17.1	300	26.5	9.4
	Iquique	−20	130	23.4	15.3	−8.1	16.7	360	27.2	10.5
Europe Africa	Porto	41	340	15.0	15.6	0.6	16.0	170	16.8	0.8
	Casablanca	34	190	19.0	17.9	−1.1	17.8	250	21.1	3.3
	Agadir	30	120	21.0	19.2	−1.8	19.1	200	23.4	4.3
	Dakar	15	–	26.1	22.4	−3.7	23.9	350	27.1	3.2
	Pointe Noire	−5	–	26.3	23.0	−3.3	23.3	300	28.0	4.7
	Lobito	−13	140	25.2	19.8	−5.4	22.1	250	26.3	4.2
	Walvis Bay	−23	170	22.4	15.3	−7.1	14.7	260	27.6	12.9
	Cape Columbine	−33	130	18.0	13.3	−4.7	11.7	220	18.1	6.4
India	Bombay	19	90	25.1	24.6	−0.5	25.2	275	27.7	2.5
Australia	Pt Hedland	−21	–	23.1	24.2	1.1	24.7	260	26.9	2.2
	Learmouth	−23	–	22.4	22.6	0.2	23.2	380	27.4	4.2
	Geraldton	−29	–	19.9	19.5	−0.4	19.6	140	21.2	1.6
	Perth	−32	–	18.5	18.4	−0.1	18.0	150	19.2	1.2

west coasts in the Americas, Europe, Africa, India and Australia. Each transect includes data from at least four stations within a 2-degree swath, and generally more than ten stations. The results are all like Fig. 4. Values of ridge temperature Tr are shown in Fig. 5 and Table 2. The diagram shows that thermal ridges in the tropics are remarkably uniform, at 28.4 °C.

Values of the littoral warming [Tr−Tcw] from Table 2 are roughly in proportion to the cooling of adjacent coastal waters below the zonal mean [Tm−Tsw]. The relationship (for which the correlation coefficient is 0.87) is this:

$$[\mathrm{Tr}-\mathrm{Tcw}] = 1.03[\mathrm{Tm}-\mathrm{Tsw}] + 1.95\ \mathrm{K} \qquad (3)$$

In other words, a large negative SST anomaly [Tm−Tsw] implies great littoral warming (Table 3). Also, the constant (1.95 K) on the right side of Eq. 3 implies that a fringe can exist even with a small *positive* SST anomaly, e.g. near Port Hedland in Australia (Table 2).

Table 3. The relationships between the littoral warming [Tr−Tcw] and the fringe width F, the distance from the shore to the first mountain range R, and the SST anomaly [Tsw−Tm]. The 16 cases with high mountains near the west coast, of the 22 involved in Table 2, have been ranked according to littoral warming and then grouped into three classes, each of 5 or 6 cases. The average for each variable is given for each class

	Littoral warming: [Tr−Tcw]		
Variable	Small	Medium	Large
[Tr−Tcw]: K	2.0	4.2	9.1
F: km	259	270	352
R: km	170	140	135
[Tsw−Tm]: K	−0.5	−2.8	−5.6

The latitudinal variation of the west-coast littoral warming [Tr−Tcw] is graphed in Fig. 6. This shows that values for the two hemispheres hinge about 5–10° N, in accordance with the hemisphere differences mentioned in Section 3.1. Also that [Tr−Tcw] is small on the west coast

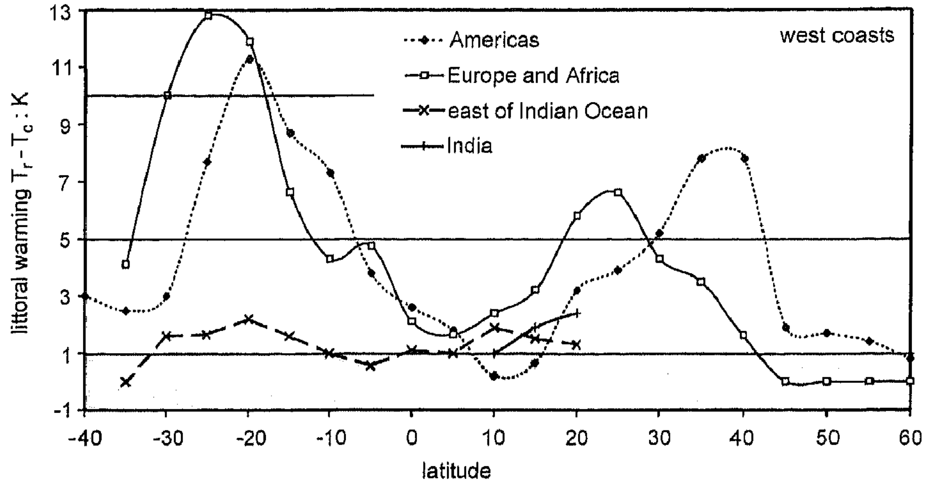

Fig. 6. The variation with latitude of the littoral warming [Tr−Tcw] across west-coast fringes

of Australia and near the equator, places where [Tm−Tsw] is small. Likewise, fringes are weak or absent poleward of 33° S and 43° N.

The effect of a mountain range on the amount of littoral warming is hinted at in Table 3. The table mentions topography in terms of R, the distance from the west coast to the nearest weather station at least 1,000 m above sea level. There may be a slight tendency for a mountain range near the coast (i.e. R is small) to enhance the warming.

3.6 The fringe width, F

Figure 4 indicates that the fringe width F cannot be gauged exactly, because of the shortage of measuring stations. Also because of the choice of lapse rate in adjusting observed temperatures (Section 3.4). Nevertheless, Table 3 does show some relationship between F and the littoral warming [Tr−Tcw], as might be expected – the wider the fringe, the greater the temperature difference across it. However, average values in Table 3 suggest that the relationship is far from proportional, so that data from all 22 cases mentioned in Table 2 lead to a linear correlation coefficient of only 0.42. The fringe width is within a factor of two of 70 times [Tr−Tcw].

It might be thought that the scatter is due to the presence of mountains. But in six of the 22 cases in Table 2 there is no land above 1,000 m within the fringe, showing that mountains are not necessary for a fringe to occur. Where there are such mountains within the fringe (i.e. F exceeds R), we can group the five cases of greatest R (with an average of 286 km) and the five of least R, where the distance of high land from the shore averages 94 km; the respective mean fringe widths are 330 km and 289 km, which are very similar. In other words, the existence or position of mountains makes little difference to fringe width.

A procedure for assessing the fringe width involves plotting F values from Table 2 against the latitude for each of the continents, with

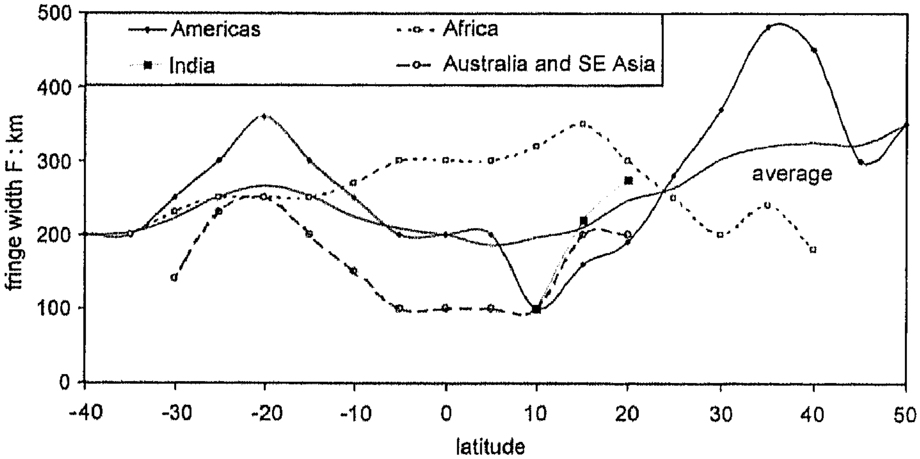

Fig. 7. The variation with latitude of the fringe width F, derived from the data in Table 2. The bold line is the average for the three continents

sufficient interpolation subsequently to provide continuous curves. The outcome is Fig. 7. The approximate average curve can be represented by the following equations, where L is the latitude (in degrees, and here taken as positive in both hemispheres)–

northern hemisphere: $F = 165 + 3.9L$ km (4a)

southern hemisphere: $F = 190 + 5.8L - 0.15L^2$ (4b)

The best agreement between continents occurs at subtropical latitudes, where littoral warming happens to be most (Fig. 6).

4. Inland cooling

Figure 4 shows eastward 'inland cooling' beyond the fringe, which is related to the difference between temperatures on opposite sides of a continent [Tcw–Tce], mentioned in Section 3.3. The cooling is shown in Fig. 8 also, which indicates approximately linear falls of the adjusted annual-mean temperature eastwards. The cooling rate C, may be expressed in units of degrees Kelvin per megametre (i.e. thousand kilometres) or K/Mm. It is convenient to regard the cooling rate as constant across any west-to-east transect, though in fact the rate may become either slightly less towards the east coast (Fig. 8), or more rapid, as near the east coast of Australia.

Additional rates of inland cooling were determined in other ways. Firstly we derived seven values from graphs like Fig. 4. They were taken across India at 19° N, Chile at 20° S, Australia at 23° S, North America at 37° N, Europe at 47° N and Canada at 50° N. Secondly, adjusted annual mean temperatures were calculated from at least five stations at each of eleven various latitudes and continents. (The median cooling rate at the six lowest latitudes is 0.3 K/Mm, but 1.7 K/Mm at the five highest latitudes.) All the above data are denoted by open symbols in Fig. 9. Thirdly, a systematic study was made of the cooling across each continent at five-degree intervals of latitude: for each latitude, a comparison was made between pairs of temperatures at about 100 km from west and east coasts, respectively. Data from this study are shown in Fig. 9 by solid squares, diamonds and circles, and prove to be in good agreement with the other data.

Overall, the cooling rate is represented by the solid line in Fig. 9. It happens to be similar in shape to the average curve for fringe width in Fig. 7. It can be represented by the following rules (where L is the latitude in degrees) and here taken as positive in both hemispheres:

northern hemisphere:

$$C = 0.03L - 0.2 \quad (5a)$$

southern hemisphere:

$$C = 0.018L - 0.0042L^2 - 1 \quad (5b)$$

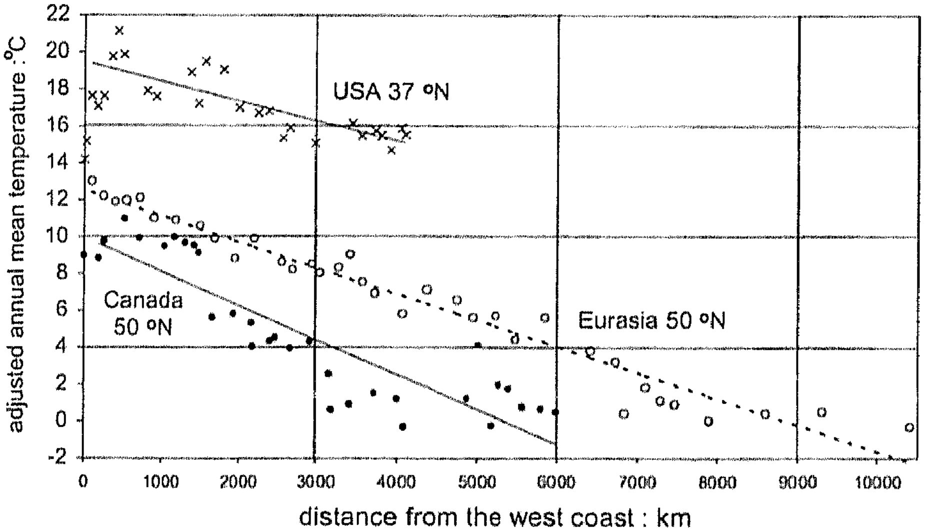

Fig. 8. The variation of the adjusted annual-mean temperature with distance from the west coast at either 48.5–51.5° N (Canada & Eurasia) or 36–38° N (USA)

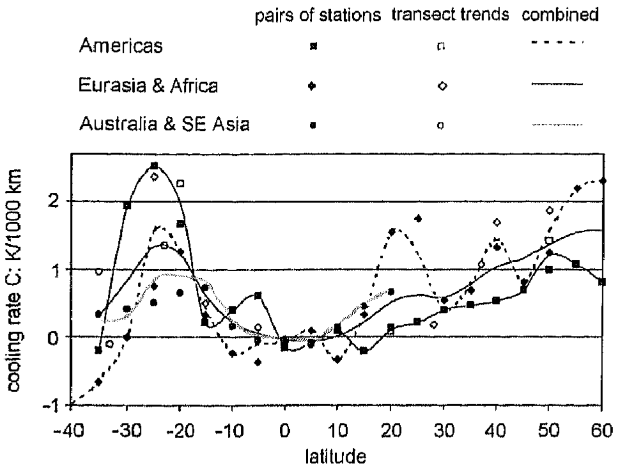

Fig. 9. The variation with latitude and continent of the cooling rate C (K/Mm) from west to east inland. The open 'transect-trends' symbols are explained in the text; they refer to the cooling from the ridge temperature Tr. The 'pair of stations' symbols come from temperatures at only two places each, respectively about 100 km from west and east coasts, so these yield very slight underestimates of C. The solid line is the three-point running mean based on both types of estimate for all continents

The character of inland cooling differs from that of the littoral warming discussed in Sections 3.4 and 3.5. Significant inland cooling occurs mainly at high latitudes in the northern hemisphere and around the Tropic of Capricorn, whereas appreciable littoral warming is found only at latitudes around 30 degrees. Neither warming nor cooling across the land is significant near the equator, where Fig. 2 shows relatively uniform temperatures across both land and sea.

The rate of littoral warming [Tr–Tcw]/F is typically 14 K/Mm (since F approximates to 70 [Tr–Tcw] km, Section 3.6), which is an order of magnitude greater than inland cooling rates C. On the other hand, the extent of inland cooling may be more than an order of magnitude larger than the fringe width F, so the warming and cooling processes tend to be comparable in their opposite effects on annual mean temperatures.

5. Results of estimating the annual mean temperature

5.1 General

Three methods are offered for estimating the annual mean temperature of places on land between 40° S–60° N. We will consider them in order of increasing simplicity. Firstly, the 'look-up method' (Section 5.2) involves a table which summarises information on Tcw, Tce, Tr, F and C for each continent, presented in earlier parts of the paper. Secondly, the 'SST method' (Section 5.3) assumes that Tcw and Tce are largely determined by the adjacent coastal sea-surface temperature (SST), and ignores differences between continents as regards Tr, F and C. For both those methods, we assume zero width for the thermal ridge and linear variations of adjusted temperatures within the zones of littoral warming and inland cooling. Also we assume no fringe on an east coast. Thirdly, the simplest method (Section 5.4) ignores everything but latitude, elevation and hemisphere in estimating the annual mean temperature.

The circularity of making estimates for the same places as those of the measurements on which the estimation is based has been avoided by using data from different places for the model design and validation, respectively. The design (i.e. the considerations in previous Sections of this paper) involved observations from about 320 stations of the 6,371 listed in the International Station Meteorological Climate Summary, whilst validation involved a different sample of 48 places from the same large pool.

The 48 places fall into three categories:

Case A – 19 places within a west-coast fringe,
Case B – 12 places outside the fringe but still nearer the west coast than the east,
Case C – 17 places nearer the east than the west coast.

5.2 Estimation of the annual mean temperature by means of a look-up table

The look-up table to use for the first method of estimating annual mean temperatures is Table 4, derived empirically from the data surveyed in previous Sections, according to hemisphere, continent, west or east coast, and latitude. Values of Tcw and Tce are taken from Fig. 3, and west-coast ridge temperatures Tr are from Fig. 5. Hence one derives [Tr–Tcw], the west-coast littoral warming. The fringe width F(km) is derived from Fig. 7, but cannot be greater than half the width of the continent. Inland cooling rates C are taken from Fig. 9.

Table 4. Look-up table for estimating annual mean temperatures. To obtain a value for a latitude not listed, use linear interpolation between values at the two nearest latitudes

West coast Continent	Latitude L: degrees	Coast temp. Tcw: °C	Ridge temp. Tr: °C	Fringe width F: km	Cooling rate C: K/Mm	**East coast** Continent	Coast temp. Tce: °C
North America	60	4.3	5.1	–	2.3	North America	−6.2
"	55	6.6	8.0	–	2.2	"	−2.1
"	50	8.9	10.6	350	1.6	"	1.0
"	45	10.8	12.7	300	0.8	"	6.7
"	40	11.3	19.1	450	1.4	"	12.3
"	35	13.7	21.5	480	0.8	"	18.4
"	30	17.2	22.4	370	0.4	"	21.1
"	25	21.2	25.1	280	1.2	"	23.6
"	20	25.2	28.4	190	1.6	"	26.1
"	15	26.6	27.2	160	0.3	"	27.0
South America	10	27.9	28.1	100	−0.3	South America	27.8
"	5	27.0	28.8	200	0.1	"	27.5
"	0	26.1	28.7	200	−0.1	"	27.2
"	−5	23.2	27.0	200	−0.1	"	26.7
"	−10	20.3	27.6	250	−0.2	"	26.1
"	−15	19.1	27.8	300	0.4	"	25.3
"	−20	17.9	29.2	360	1.3	"	24.5
"	−25	16.7	24.4	300	1.6	"	22.7
"	−30	17.6	20.6	250	0.0	"	20.8
"	−35	14.1	16.6	200	−0.7	"	17.7
"	−40	10.6	13.6	200	−1.2	"	13.5
Europe	60	7.5	7.5	–	0.8	Asia	−2.0
"	55	9.0	9.0	–	1.1	"	−0.7
"	50	11.4	11.4	–	1.2	"	0.6
"	45	13.8	13.8	–	0.7	"	5.9
"	40	15.1	16.7	180	0.5	"	11.2
Africa	35	17.1	20.6	240	0.5	"	14.0
"	30	19.1	23.4	200	0.4	"	16.7
"	25	21.0	27.6	250	0.2	"	20.5
"	20	22.9	28.7	300	0.1	Africa	30.0
"	15	25.1	28.3	350	−0.2	"	30.1
"	10	27.3	29.7	320	0.1	"	30.2
"	5	26.5	28.1	300	−0.1	"	28.3
"	0	25.6	27.7	300	−0.2	"	26.4
"	−5	25.0	29.7	300	0.6	"	26.1
"	−10	24.3	28.6	270	0.4	"	25.7
"	−15	21.0	27.6	250	0.2	"	25.4
"	−20	17.6	29.5	250	2.0	"	25.1
"	−25	16.2	29.0	250	2.5	"	23.1
"	−30	14.8	24.8	230	1.9	"	21.1
"	−35	17.3	20.4	200	−0.2	"	18.2
India	20	26.9	29.3	275	1.9	India	28.0
"	15	27.5	29.4	220	1.5	"	28.5
"	10	27.5	28.5	100	1.2	"	28.7
S.E.Asia	20	26.1	27.4	200	0.7	S.E.Asia	24.3
"	15	26.5	28.0	200	0.5	"	26.4
"	10	26.9	28.8	100	0.2	"	28.5
"	5	26.8	27.8	100	−0.1	"	27.7
"	0	26.7	27.8	100	0.0	"	26.9
"	−5	27.5	28.0	100	−0.1	"	27.3
Australia	−10	28.2	29.2	150	0.2	Australia	27.6
"	−15	27.2	28.8	200	0.7	"	25.4
"	−20	26.2	28.4	250	0.9	"	23.2
"	−25	23.0	24.6	230	0.8	"	21.0
"	−30	19.7	21.3	140	0.3	"	18.2
"	−35	18.0	18.0	–	0.2	"	15.7
"	−40	13.4	13.4	–	−0.2	"	13.7

Table 5. Estimates of the annual mean temperatures Tes at 48 selected places, using Table 4. The 'input' variables mentioned in the first four columns are the location, latitude (L degrees), elevation h (metres) and zonal distance inland D (km). The next column shows the observed annual mean temperature Tp. Table 4 provided values of the ridge temperature Tr, fringe width F, littoral warming [Tr−Tcw] and cooling rate C (K/Mm), to estimate Tes, shown in the penultimate column. The difference [Tes−Tp] is the estimate's error, shown as ΔT in the last column. A negative error means an *under*-estimate

A: places within the west-coast fringe

Location: city, country	L: degrees	h: m	D: km	Tp: °C	Tr: °C	F: km	[Tr−Tcw]: K	Tes: °C	ΔT: K
La Rochelle, France	46.1	10	1	12.8	13.2	–	0.0	13.2	0.4
Portland, USA	45.6	6	105	12.2	12.4	306	1.9	11.2	−1.0
Lisbon, Portugal	38.8	123	15	16.1	17.6	200	2.2	14.9	−1.2
Beirut, Lebanon	33.8	19	12	20.0	21.3	226	3.8	17.6	−2.4
Casablanca, Morocco	33.5	62	10	17.8	21.4	228	3.7	17.6	−0.2
Jerusalem, Israel	31.9	759	50	16.1	22.3	215	4.0	15.5	−0.6
Bombay, India	19.1	14	3	27.2	29.3	265	2.3	27.0	−0.2
Dakar, Senegal	14.7	24	2	24.4	28.4	348	3.2	25.1	0.7
San Salvador, El Salvador	13.7	621	60	24.4	27.4	144	0.5	24.0	−0.4
Matadi, Congo	−5.8	356	140	26.7	29.5	295	4.7	25.3	−1.4
Broome, Australia	−18.0	18	1	26.8	28.6	230	2.0	26.5	−0.3
Pt. Hedland, Australia	−20.3	7	1	26.4	28.4	250	2.2	26.2	−0.2
Antofagasta, Chile	−23.5	120	7	17.2	25.8	318	8.8	16.7	−0.5
Carnarvon, Australia	−24.9	4	2	22.0	24.6	230	1.7	22.9	0.9
Geraldton, Australia	−28.8	38	3	20.0	22.1	162	1.6	20.3	0.3
Perth, Australia	−31.9	12	16	18.5	20.0	140	1.0	19.1	0.6
Santiago, Chile	−33.4	474	82	14.4	17.9	216	2.7	13.9	−0.5
Cape Town, South Africa	−34.0	42	6	17.2	21.3	206	4.5	16.7	−0.5
Mt Gambier, Australia	−37.8	64	35	14.4	15.4	–	0.0	15.1	0.7

B: inland places, but closer to a west coast

Location (city, country)	L: degrees	h: metres	D: km	Tp: °C	Tr: °C	F: km	C: K/Mm	Tes: °C	ΔT: K
Moscow, Russia	56.0	190	1800	4.4	8.7	–	1.0	5.9	1.5
Krakow, Poland	50.0	220	1300	7.5	11.4	–	1.2	8.7	1.2
Paris, France	48.7	96	280	11.1	12.0	–	1.1	11.2	0.1
Budapest, Hungary	47.4	185	1540	10.6	12.6	–	0.9	10.3	−0.3
Laramie, USA	41.3	2221	1540	5.0	17.4	433	1.3	4.9	−0.1
Denver, USA	39.8	1612	1600	10.6	19.2	480	1.4	9.6	−1.0
Beirut, Lebanon	33.8	19	3640	20.0	21.3	230	0.5	19.6	−0.4
Jerusalem, Israel	31.9	759	3700	16.1	22.3	215	0.4	17.1	1.0
Mexico City, Mexico	19.4	2234	600	16.7	28.3	186	1.4	16.5	−0.2
Timbuktu, Mali	16.8	299	1200	27.7	28.4	332	−0.1	27.0	−0.7
Lagos, Nigeria	6.6	40	1550	27.2	28.6	306	0.0	28.4	1.2
Alice Springs, Australia	−23.8	544	2079	21.1	25.5	235	0.8	21.3	0.2

Table 5 (continued)

C: places closer to an east coast

Location (city, country)	L: degrees	h: metres	De: km	Tp: °C	Tce: °C	C: K/Mm	Tes: °C	ΔT: K
Ulaan Baatar, Mongolia	48.0	1316	2300	−0.4	2.7	0.8	−2.0	−1.6
St John's, Canada	47.6	140	1	5.0	4.7	1.2	4.0	−1.0
Chicago, USA	42.0	250	1400	10.0	10.0	1.2	10.5	0.5
Beijing, China	40.0	55	930	12.8	11.2	0.6	11.4	−1.4
New Orleans, USA	30.0	1	807	20.9	21.1	0.4	21.4	0.5
Miami, USA	25.8	4	10	24.4	23.2	1.1	23.2	−1.2
Hong Kong, China	22.2	24	5	23.9	22.6	0.7	22.5	−1.4
Madras, India	13.0	16	5	28.9	28.6	1.4	28.5	−0.4
Belem, Brazil	−1.4	16	200	27.2	27.0	−0.1	26.9	−0.3
Jakarta, Indonesia	−6.3	30	20	27.2	28.3	−0.1	28.1	0.9
Dar Es Salaam, Tanzania	−6.9	55	10	26.4	27.5	0.5	27.3	0.9
Lusaka, Zambia	−15.3	1154	1300	21.1	25.4	0.2	19.9	−1.2
Asuncion, Paraguay	−25.3	101	935	23.3	22.2	1.6	23.2	−0.1
Durban, S. Africa	−30.0	8	2	21.1	21.1	1.9	21.1	0.0
Sydney, Australia	−33.8	15	6	17.8	19.2	0.2	19.1	1.3
Buenos Aires, Argentina	−34.8	20	10	16.7	17.4	−0.7	17.3	0.6
Canberra, Australia	−35.3	577	85	13.3	15.8	0.2	12.9	−0.4

If the place is within the fringe (**Case A**), its estimated adjusted temperature (Tes) is given by the following equation, where D(km) is the distance from the western shore, h (*metres*) the elevation, and values of Tcw, [Tr−Tcw] and F(km) come from Table 4 for the appropriate latitude and continent:

$$\mathrm{Tes} = \mathrm{Tcw} + \mathrm{D}[\mathrm{Tr}-\mathrm{Tcw}]/\mathrm{F} - 5\,\mathrm{h}/1000 \qquad (6a)$$

If the distance D(km) exceeds F (**Case B**), the following applies, where C is the inland cooling rate (K/Mm), and Tr, F(km) and C(K/km) come from Table 4:

$$\mathrm{Tes} = \mathrm{Tr} - (\mathrm{D}-\mathrm{F})\mathrm{C}/1000 - 5\,\mathrm{h}/1000 \qquad (6b)$$

If the place is nearer the *east* coast (**Case C**), but distant De(km) from it, use Eq. (6c), where Tce is the shoreline temperature on the east coast, derived from Fig. 3:

$$\mathrm{Tes} = \mathrm{Tce} + \mathrm{C}\cdot\mathrm{De}/1000 - 5\,\mathrm{h}/1000 \qquad (6c)$$

The method outlined above has been applied to the 48 places named in Table 5. As an example, take the case of Ulaan Baatar at an elevation of 1316 m in Mongolia. It is a Case C, and 2,300 km (De) west of the east coast. Table 4 gives Tce as 2.7 °C and C as 0.8 K/Mm, in Asia at 48° N. So the estimated annual mean temperature is minus 2.0 °C. This is an underestimation of 1.6 K, since the observed value is minus 0.4 °C

The results in Table 5 have an overall average absolute error of 0.7 K, the mean bias being −0.1 K. For type C cases, the average error is 0.8 K, and for type B only 0.6 K. The sizes of the errors show no significant variation with either latitude or distance from the sea. Other aspects of the errors are discussed in Section 6.5.

5.3 Estimation of the annual mean temperature, based on coastal sea-surface temperatures

The alternative 'SST method' of estimation follows a similar path towards a figure for the annual mean temperature Tes. We use the same three expressions (Eq. 6) as in the look-up method, but this time start from Table 1 for values of the coastal sea-surface temperature (SST) instead of Table 4. Then we estimate the shoreline temperatures Tcw & Tce as functions of the coastal SST, and

Table 6. Expressions used in deriving terms for the SST method of estimating annual mean temperatures Tes

Term	Units	Source	Expression
Tcw	°C	Eqn (2a)	1.11 Tsw−2.1
Tce	°C	Eqn (2b)	1.23 Tse−5.9
Tr	°C	Fig (5)	28.4 if L < 23°, else [40−0.57 L]*
F	km	Eqn (4)	if north of the equator: 165 + 3.9 L if south of the equator*: $190 + 5.8\,L - 0.15\,L^2$
C	K/Mm	Eqn (5)	if north of the equator: −0.2 + 0.03 L if south of the equator*: $-1.0 + 0.18\,L - 0.0042\,L^2$

* L is taken as positive in both hemispheres in these expressions

Tr, F and C as functions of latitude. The relevant expressions are gathered together in Table 6.

In this method of estimating, we assume that temperatures on land are controlled mainly by the same-latitude coastal sea-surface temperature Ts, at the *nearer* coast. We ignore differences between continents, so the SST method of estimation is likely to be less accurate than using a look-up table (Section 5.2). On the other hand, there is the advantage of using values of Ts, which are directly measured, relatively accurate and readily available, unlike [Tr–Tcw], F and C.

Values of ridge temperature Tr, fringe width F, cooling rate C and shoreline temperatures (Tcw and Tce) for particular places are given in both Table 5 and Table 7, and may be compared. Any differences arise from the alternative methods of derivation.

The outcome of Table 7 is that the last column indicates an average absolute error of 1.0 K, which is slightly larger than the 0.7 K obtained by the look-up method of estimation. The mean bias here is −0.2 K, instead of −0.1 K.

Table 7 also shows that the SST method gives the temperature at type A places more accurately than at type C places, the mean absolute errors of Tes being 0.7 K and 1.4 K, respectively. This is because the uncertainty in Eq. (2b) (relating Tce to Tse) is larger than that for Eq. (2a) (relating Tcw to Tsw), as mentioned in Section 3.3.

5.4 Estimation of the annual mean temperature from the zonal mean

Equation (1) provides a figure for the zonal mean temperature Tm at a place in either hemisphere and any latitude between 40° S–60° N, after allowance is made for elevation. In the case of New Orleans, for instance, the equation yields 21.0 °C, which is an over-estimate by only +0.1 K. For all the 48 cases listed in Table 5, the mean absolute error is 1.5 K.

6. Discussion

The empirical information in preceding Sections gives rise to many questions about causes. Here are some preliminary considerations.

6.1 The littoral fringe

The littoral fringe is due to processes of adjustment between incoming marine air and the energy balance on land. Differences between the respective temperatures of the sea surface and the adjacent land create sea breezes which carry cool air inland in the daytime. However, sea breezes affect only places less than 75 km or so from the shore. This is the distance within which the cool winds prevent the 'normal' daily maximum temperature being reached, because the highest speed of a sea-breeze front is about 15 km/h (Linacre and Barrero, 1974; Simpson, 1994), and daily temperature maxima are reached about 5 hours later than the time of a sea breeze's onset at the shore (LG97, p. 299). That distance of 75 km is less than average fringe widths mentioned in Table 3. But, apart from daytime sea breezes, the fringe may be extended inland also by all-day incursions of cool maritime air whenever the gradient wind is directed onshore.

The occurrence of littoral warming [Tr−Tcw] is related primarily to particularly cold waters against the shore, colder than the zonal mean (which itself is largely governed by the temperatures of the seas that cover 70% of the globe).

Table 7. Estimates of annual mean screen temperature Tes at the places mentioned in Table 5, obtained by the SST method. See Table 1 for the sea-surface annual mean temperatures Tsw and Tse. See Table 5 for the geographic information (latitude L, elevation h, and either D or De – the distances west or east, respectively, to the sea) and the observed temperatures Tp. Table 6 provided values of the coastal onshore temperatures Tcw and Tce, the ridge temperature Tr, the fringe width F and the cooling rate C. The last column shows ΔT, i.e. the estimate's error [Tes−Tp]

A: places within the west-coast fringe

Location: city, country	Tsw: °C	Tcw: °C	Tr: °C	F: km	Tes: °C	ΔT: K
La Rochelle, France	14.4	13.8	13.8	–	13.7	0.9
Portland, USA	11.3	10.4	14.0	343	11.5	−0.7
Lisbon, Portugal	16.8	16.6	17.9	316	16.0	−0.1
Beirut, Lebanon	18.2	18.1	20.7	297	18.1	−1.9
Casablanca, Morocco	18.3	18.2	20.9	296	18.0	0.2
Jerusalem, Israel	18.7	18.7	21.8	289	15.4	−0.7
Bombay, India	26.6	27.4	28.4	239	27.4	0.2
Dakar, Senegal	23.8	24.3	28.4	222	24.2	−0.2
San Salvador, El Salvador	26.9	27.8	28.4	218	24.8	0.4
Matadi, Congo	24.5	25.1	28.4	222	25.4	−1.3
Broome, Australia	26.5	27.3	28.4	249	27.2	0.4
Pt. Hedland, Australia	25.6	26.3	28.4	249	26.3	−0.1
Antofagasta, Chile	17.1	16.9	26.5	246	16.6	−0.6
Carnarvon, Australia	22.9	23.4	25.7	244	23.4	1.4
Geraldton, Australia	20.7	20.9	23.5	236	20.7	0.7
Perth, Australia	18.9	18.8	21.8	225	19.0	0.5
Santiago, Chile	15.5	15.1	20.9	219	14.9	0.5
Cape Town, South Africa	16.3	16.0	20.6	217	15.9	−1.3
Mt Gambier, Australia	15.3	14.9	18.4	198	15.2	0.8

B: inland places, but closer to a west coast

Location city, country	Tr: °C	F: km	C: K/Mm	Tes: °C	ΔT: K
Moscow, Russia	8.2	–	1.5	4.5	0.1
Krakow, Poland	11.6	–	1.3	8.8	1.3
Paris, France	12.3	–	1.3	11.5	0.4
Budapest, Hungary	13.0	–	1.2	10.2	−0.4
Laramie, USA	16.5	326	1.0	4.1	−0.9
Denver, USA	17.3	320	1.0	8.0	−2.6
Beirut, Lebanon	20.7	297	0.8	17.9	−2.1
Jerusalem, Israel	21.8	289	0.8	15.4	−0.7
Mexico City, Mexico	28.4	241	0.4	17.1	0.4
Timbuktu, Mali	28.4	231	0.3	26.6	−1.1
Lagos, Nigeria	28.4	191	0.0	28.2	1.0
Alice Springs, Australia	26.4	246	0.9	22.0	0.9

C: places closer to the east coast

Location city, country	Tse: °C	Tce: km	C: K/Mm	Tes: °C	ΔT: K
Ulaan Baatar, Mongolia	7.4	3.2	1.2	−0.5	−0.1
St John's, Canada	6.9	2.6	1.2	1.9	−3.1
Chicago, USA	11.4	8.1	1.1	8.4	−1.6
Beijing, China	13.0	10.1	1.0	10.7	−2.1
New Orleans, USA	25.3	25.2	0.7	25.8	4.9
Miami, USA	25.8	25.8	0.6	25.8	1.4
Hong Kong, China	22.6	21.9	0.5	21.8	−2.1
Madras, India	28.5	29.1	0.2	29.0	0.1
Belem, Brazil	26.6	26.8	−0.8	26.6	−0.6
Jakarta, Indonesia	28.0	28.5	0.0	28.4	1.2
Dar Es Salaam, Tanzania	26.2	26.3	0.0	26.1	−0.3
Lusaka, Zambia	26.0	26.1	0.8	21.3	0.2
Asuncion, Paraguay	22.4	21.7	0.9	22.0	−1.3
Durban, South Africa	22.3	21.5	0.6	21.5	0.4
Sydney, Australia	18.3	16.7	0.3	16.6	−1.2
Buenos Aires, Argentina	16.8	14.8	0.2	14.7	−2.0
Canberra, Australia	17.3	15.4	0.1	12.5	−0.8

The effect of west-coastal waters being colder at Tsw than the zonal mean temperature Tm is shown in Table 3. An increase of [Tm−Tsw] from 0.5 K to 5.6 K is associated with an increase of warming on land from 2.0 K to 9.1 K. So the littoral warming is of the order 1.4 times the offshore cooling, on average. In other words, the warming *more* than compensates for any previous cooling of onshore winds. As a result, the average ridge temperature Tr (Table 6) is about 3.1 K *higher* than the zonal mean at 40° S (Eq. 1), 5.0 K more at 20° S, 0.6 K at the equator, 3.7 K at 20° N, 1.6 K at 40° N and 2.7 K at 50° N, i.e. most at the Tropics. This latitudinal variation of overshoots is like that of the difference between zonal mean precipitation and evaporation (LG97, p. 198). The overshoot is more where potential evaporation exceeds rainfall, notably at the Tropics. There, inland climates tend to be arid and hot, because of prevailing subsidence of the atmosphere.

A practical consequence of the existence of coastal fringes, where temperature patterns are distinctly different from those further inland, is that it may not be valid to lump the two regions together for statistically relating climate to geography. The occurrence of fringes is sufficiently consistent and significant, and they are so distinct, that they should be included in spatial climate analysis (e.g., Zheng and Basher, 1996; Agnew and Palutikov, 2000).

Another point is that many large cities lie within the west-coast fringe of a continent, and littoral warming explains the socio-economic stratification. In Sydney, San Diego and Lima, for instance, there is a gradation from the affluent cool coast to the disadvantaged hotter inland parts.

6.2 The effects of mountains

There are several possible reasons for expecting the fringe width and warming to be altered by a mountain range parallel to the coast. Examples are the Rockies in North America, the Andes, the Kalahari plateau in southern Africa, and the Deccan in India. Such a range might separate the marine air on one side from different airmasses on the other, less influenced by the sea's cooling. Secondly, coastal mountains deflect onshore winds into an equatorward direction, inducing ocean up-welling, which lowers shoreline temperatures. This effect is important in northern California, for instance. Thirdly, subsidence on the downwind side of mountains would lead directly to warming, and also to a rain-shadow with consequent warmth due to less cloud or evaporative cooling.

However, the evidence points to little impact overall of mountains on littoral warming. They are not essential for littoral warming. Table 2 includes six cases of a fringe occurring in the absence of any high coastal range, though the average littoral warming in these cases (2.8 K) is only about half that in the 16 others (i.e. 5.4 K). Where there are mountains within the fringe, there is little connection between the fringe width and the proximity of the mountains to the coast, denoted by the distance R (Table 2). For the five cases of greatest R (average 286 km) the average fringe width is 334 km, whereas for the five cases of least R (about 94 km) the average width is 291 km, which is hardly different. In conclusion, the success of estimating annual mean temperatures without considering mountains (Section 5) confirms that their effect is small.

6.3 Inland cooling

At first sight, it is surprising that annual mean temperatures decline across a continent from west to east, since east coasts at latitudes between about 10–40° are adjacent to warm currents from the equator while west coasts are generally bathed by cool equatorward ocean currents. (The exception is Australia, where the west coast is girdled by the warm, southwards Leeuwin Current.) The explanation depends on the latitude. The cooling at high latitudes in the northern hemisphere is an adjustment of westerly winds from relatively warm oceans to the temperatures fixed by the energy balance of land surfaces, which, unlike an open ocean, cool far below freezing in winter. Also, high-latitude west coasts are warmed by warm currents such as the Gulf Stream, while high-latitude east coasts are affected, to a lesser extent, by cold currents offshore, such as the Labrador and Falkland Currents. In addition, there is a tendency for polar winds to flow towards the equator in the lee (i.e. to the east) of north-south oriented mountain ranges such as the Rockies, especially in winter, and the northern hemisphere topography produces quasi-stationary waves with troughs near the east coast. The combined effect of all three factors (westerly winds, ocean currents and stationary waves in the flow aloft) is largest around 50–60° N and decreases equatorward.

The apparent weak west-to-east cooling over continents near the equator is actually an east-to-west warming of the Trade winds, due to the equilibrium temperature over land being slightly higher than that of the equatorial oceans. The latter are cooled by evaporation and coastal upwelling caused by the Trade winds (LG97, p. 230).

6.4 The effects of nearby seas

All three methods of estimation in Section 5 ignore two effects – a) that of any large enclosed sea, such as the Baltic Sea or the Black Sea, and b) the influence of a nearby north or south coast. The first issue arises in estimating the annual mean temperature of Jerusalem, for instance. If it is regarded as inside the fringe of the Mediterranean coast, there is an under-estimation by 0.6 K, whereas there is over-estimation by 1.0 K by the look-up method if Jerusalem is regarded as beyond the fringe of the Atlantic Ocean, with the presence of the Mediterranean Sea being ignored. For Beirut the respective errors are −2.4 K and −0.4 K. So, on average, it seems best to forget the existence of the Mediterranean, and, therefore of smaller seas. For example, if we leave aside the fact that Chicago is on the edge of Lake Michigan, the error is still only + 0.5 K.

Three examples in Table 5 indicate that adjacent seas north or south also have little effect on the annual mean temperature. Estimating the annual mean temperature of New Orleans from its westward distance from the North American east coast gives an error of only + 0.5 K, as though there were no Gulf of Mexico closely adjacent, to the south. Likewise for Lagos, which is 1550 km east of the Atlantic: ignoring the close proximity of the Gulf of Guinea leaves the estimation error as only + 1.2 K.

The SST method is off the mark for the case of New Orleans, for which the error in Table 7 is + 4.9 K, not because of the presence of the Gulf of Mexico to the south, but on account of the remarkably warm Gulf Stream. That makes the temperature Tce at 30° N on the Atlantic coast, estimated from the adjacent SST, appreciably higher than the actual Tce, leading to over-estimates of annual mean temperatures in south-eastern USA.

6.5 Errors of estimation

The mean absolute errors of 0.7 K, 1.0 K and 1.5 K given in Tables 5 and 7 and Section 5.4, respectively, indicate the superiority of the look-up method. But its average error is only 0.3 K less than that of the SST method, indicating that the coastal SST influences the annual mean temperature strongly, while differences between Tr, F and C in the various continents are relatively unimportant.

The 'zonal-mean' method used in Section 5.4 allows for the two dominant factors, latitude and elevation, but ignores the longitudinal variation of temperatures across a continent, i.e. the pattern of littoral warming, thermal ridge and inland cooling. Allowing for this variation in the look-up method reduces the error by about half.

The remaining estimation errors in the look-up method are then attributed to inaccuracies of measurement and to implicit assumptions, namely a) uniform temperatures within the region around each weather station (neglecting the effects of urban heating, irrigation areas, lakes and local topography, for instance), b) linear variation between tabulated values spaced at 5 degrees of latitude, c) no east-coast fringes, and d) linear variations of adjusted temperatures with distance.

The errors of estimation may be compared with the variations of annual mean temperature over a period of 30 years, the usual period of averaging in defining a climate. According to the NCAR/NCEP global reanalysis data-set, the standard deviation varies from 0.3 K at most low-latitude and coastal places, to over 2.0 K in particular areas. The latter include the northern interior of North America and Asia, and (because of El Nino's) the west coast of equatorial South America. Overall, the average standard deviation of annual means near the 48 places in Table 5 during 1968–1996 was 1.2 K. Such a figure for the scatter of annual mean temperatures is like the average estimation errors mentioned earlier, or greater.

Finally, we must bear in mind the effect of global warming. It will eventually necessitate revision of the look-up table (Table 4) and the expressions in Table 6.

7. Conclusions

7.1. A review of the lapse rates of surface-air temperatures on high land indicates a range of values with a median of 5 K/km. This is used to 'adjust' observed values of annual mean temperatures to sea-level equivalents. Likewise, zonal-mean sea-level temperatures tend to fall with latitude L according to L^2, so the temperature gradient with latitude is about 0.016 L K/°lat, and this allows 'correction' of temperatures to their equivalents at a common latitude. Consequently, we have a useful basis for analysis of the variation of annual-mean temperature eastward or westward from continental coasts.

7.2. West-coast weather stations close to the shore tend to have annual mean temperatures within a degree or so of those of the surface of the adjacent ocean Ts. But Ts off east coasts is often several degrees higher than the shoreline weather station temperature, especially at high latitudes.

7.3. West coasts, especially around the Tropics, are characterised by a considerable initial increase of adjusted temperature away from the coast towards the inland, across a 'littoral fringe'. Its width is commonly 200–400 km. At the inland edge is a 'thermal ridge', with adjusted temperatures as much as 10 K higher than those at the coast. This 'littoral warming' is greatest where the sea-surface temperature at the coast is most below the zonal mean temperature for the particular latitude. The warming exceeds the previous offshore cooling. It is increased if there are high mountains near the west coast, but the absence of mountains does not prevent there being a fringe. Also, the width of the fringe appears to be independent of the proximity of mountains to the sea.

7.4. Adjusted annual mean temperatures further inland than any fringe tend to fall roughly linearly with distance eastwards; the decline starts at the west coast if there is no fringe. The rate of fall with distance is approximately proportional to the latitude in the northern hemisphere, but the variation with latitude is more complicated in the south. In either case, the rate of inland cooling is typically an order of magnitude smaller than the rate of littoral warming, though the cooling may extend over a far greater distance.

7.5. On the basis of the exploration of zonal patterns of adjusted temperatures, estimates have been made of the annual mean temperatures of 48 places in three ways. The overall average error of the estimates is 0.7 K (using the look-up method), 1.0 K (using the SST method) and 1.5 K (for the zonal-mean method). The comparison shows the importance of the zonal pattern of fringe warming and inland cooling.

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