MET.O.14

METEOROLOGICAL OFFICE
BOUNDARY LAYER RESEARCH BRANCH
TURBULENCE & DIFFUSION NOTE

T.D.N. No. 56

Convection over the sea*

by N Thompson

June 1974

* based on contribution to Air-Sea Interaction Symposium, IAMP/IAPSO Combined First Special Assemblies, 14-25 January 1974, Melbourne, Australia.

FHI

Convection over the Sea*

by N Thompson

* based on contribution to Air-Sea Interaction Symposium, IAMAP/IAPSO Combined First Special Assemblies, 14-25 January 1974, Melbourne, Australia.

TDN No. 56
June 1974

Convection Over The Sea

By N Thompson

Summary

Observations of turbulent fluctuations of wind, temperature and humidity at heights between 50 and 200m by a tethered balloon system are used to describe some features of shallow moist convective boundary layers over the open sea in middle latitudes. The data have been analysed to give vertical fluxes of heat and water vapour and spectral correlations of temperature and humidity. The importance of the water vapour flux in maintaining convection is verified and evidence is provided which suggests that the rate of warming of a moist convective layer topped by a marked inversion is strongly dependent on this vapour flux. Correlations between temperature and humidity differ very markedly from those obtained nearer the surface by other workers. This and other evidence support a marked coupling between cloud and sub-cloud processes even in comparatively weak convection.

1. Introduction

There have been comparatively few studies of the structure and evolution of the convective boundary layer over the sea but similar investigations over land are more numerous and from them a clearer picture is beginning to emerge of the role of the vertical heat flux in maintaining the vertical temperature structure. For a boundary layer 1 or 2,000m thick the convective mixing around midday is rapid enough for the heating rate to be roughly constant at all heights so the vertical gradient of heat flux is constant also (Lenschow 1970). The buoyant thermals bombard the capping inversion and entrain heat downwards by a process which is not yet fully understood but which depends certainly on factors such as the presence or absence of wind shear across the interface (Readings et al. 1973). The turbulent kinetic energy generated by the buoyancy forces is not all dissipated locally and some is exported to the upper part of the boundary layer where presumably it assists in the downward mixing of entrained heat. There appears to be a rough proportionality between rate of heat entrainment and the surface heat flux, the factor being about 0.25 on average though there is some evidence that it may vary with state of development of the boundary layer (Carson 1973).

Moist convection has a substantially different structure. If there is no condensation a useful approximation may be to assume that the virtual heat flux shows the same sort of variation with height as the heat flux does in the dry case. If the boundary layer is being steadily heated and moistened and radiative effects are neglected then both heat and water vapour fluxes decrease uniformly with height. The interfacial mixing now entrains warmer and usually drier air so although the heat flux is again downwards at the inversion the vapour flux is still upwards at this level. Hence the vapour flux plays an increasingly important part in the maintenance of upward buoyancy forces as the height increases. It follows from this that the vertical gradient of the (sensible) heat flux is greater than in the dry convective case, and the flux changes sign at a lower height therefore.

Further complexity is introduced in the structure of the boundary layer once the convective process involves condensation. The mixing and transfer are now on a more organised basis and because of the large horizontal inhomogeneity a statistical description of the structure can give only the crudest indication of the processes taking place. The vertical ordering is now into two layers, cloud and subcloud, and of these the former in particular is horizontally divided into distinct "between-cloud" and "in-cloud" regimes. A horizontal ordering is also appropriate for the subcloud region, chiefly in its upper part in comparatively undisturbed conditions but with deeper convection the cloud-subcloud interactions may directly extend from surface to top of the boundary layer. It is no longer reasonable to ignore effects of radiational cooling or to approximate them by assuming that they lead to more or less equal rates of cooling throughout the boundary layer.

Large-scale motion between clouds in the cloud layer is predominately sinking and turbulent entrainment across the capping inversion is largely confined to the vicinity of the cloud tops. In the upper part of the boundary layer the buoyancy forces are enhanced considerably by the release of latent heat and the rate of entrainment must therefore be comparatively large locally. The resulting localised downward injections of heat will be smoothed out to some extent when they assist in evaporation of the cumulus cloud droplets but in spite of this there will be considerable horizontal variation of the vertical heat flux. In general then the thermodynamic structure of this moist convective boundary layer appears to bear little resemblance to the dry thermally-driven one.

In order to study experimentally the convective layer over the open sea in an effective way an observational array is needed with high vertical resolution and either high resolution horizontally or else continuous measurements. Radio-sonde and radar techniques can provide only a small fraction of the required information and single aircraft fail to give vertical resolution. However tethered balloon systems can go a considerable way towards meeting the observational requirements, at least in the lower part of the boundary layer. A number of such systems have been deployed operationally (e.g. Vasilchenko et al (1962), Yokoyama et al (1969), Garstang et al (1971), Thompson (1972)) and in the GATE experiment this year five different agencies are equipping a total of seven of the participating ships in this way. The advantages to be gained by the use of such systems are considerable. For example long time-series of observations of wind velocity, temperature and humidity may be made at several levels simultaneously at locations remote from land and since in favourable conditions the data can be obtained at heights in excess of 1,000m it is possible to use the observations to gain considerable insight into processes such as cloud-sub-cloud interactions. Additionally in major experiments such as GATE where balloons are deployed from several ships the wind data can be used to calculate divergences with high accuracy in the layer near the surface where conventional wind-finding methods or sondes cannot provide sufficient time and vertical resolution. The technique is exploited more fully when measurements of vertical as well as horizontal wind components are made but as yet most tethered systems have measured only the horizontal component.

A major shortcoming of the tethered balloon technique apart from cumbersomeness and hence inconvenience in use is that it does not provide a stable platform for the sensors. The outputs from these include spurious contributions caused by first the characteristic periodic crosswind migrations of the balloon and second by predominantly vertical motion of the tethering point produced by pitching of the ship. Motions of the first kind can produce significant errors in vertical momentum fluxes calculated from eddy correlation of measured horizontal and vertical wind speed (Thompson 1969) and are difficult to filter out because they occur at frequencies which are typically well within the energy-containing region of the cospectrum. The effects of ship motion are most noticeable at frequencies usually somewhat higher than about 0.1Hz and although very severe can be smoothed out fairly successfully without significant attenuation of measured fluxes if the sensors are at heights of 50m or more. The spectra will be more seriously influenced by ship motion because here the spurious contributions will appear normally in regions with high spectral density. Both horizontal and vertical velocity spectra will be affected since the ship motion results in alternate stretching and relaxing of the balloon cable catenary with resulting horizontal as well as vertical motion.

The spurious contributions to the measured temperatures and humidity fluctuations which are caused by horizontal sensor motion will be small usually and in general their only significant effect will be to produce phase errors which vitiate the Taylor transformation $k = 2\pi n/\overline{U}$ at frequencies around or above those of the ship motion (Thompson 1973) with resulting distortion of the spectra, usually in the inertial subrange of frequencies. Rough similarity arguments (Thompson 1972) predict that the vertical sensor motion will produce greater "noise" in the temperature than humidity signals. The humidity data will often be insignificantly affected because measurements of meteorological interest (i.e. those in convective conditions) are usually made in the region of the atmosphere where the humidity gradient is small.

A considerable improvement in the signal to noise ratio could be obtained by using an inertial platform to monitor the sensor motion or alternatively by servostabilising the tethering point of the balloon cable on the ship. The first of these solutions makes the measuring system much more complex and heavier and is not really practicable at sea where the balloon used is relatively small but the second is more feasible and will be adopted by at least one ship during GATE. However even without such attempts to reduce the effects of ship motion it is possible in moderate seas (winds less than about $10ms^{-1}$) to obtain useful data using comparatively simple systems such as that described by Thompson (1972, 1973) from which plausible estimates of vertical fluxes of heat, water vapour and (to a lesser degree) momentum may be obtained.

The remainder of this note discusses certain aspects of moist convection revealed by data obtained using a tethered balloon system near OWS "Juliett" during June 1970.

2. Instrumentation

Turbulence sensors were attached at one or two levels to the cable of a tethered balloon flown from HMS HECLA. Measured parameters were magnitude of the wind vector, wind inclination to the horizontal, temperature and wet-bulb depression. The sensor outputs were converted to audio-frequency multiplexes before transmission, and recorded on analogue magnetic tape. Full details are given by Thompson (1972, 1973).

3. Data and data processing

Measurements were made during JASIN 70, an air-sea interaction experiment near OWS "J" (52N, 20W) in June 1970 (Royal Society 1971). The data to be discussed were obtained in convective conditions during the latter-half of the expedition, on five separate days. The height of the convective boundary layer during the observational periods was less than 2000m but the period spanning the observations was synoptically disturbed. Data processing involved replay, demultiplexing, frequency-to-voltage conversion and low-pass filtering (cut-off at 0.5Hz, slope 24db/octave) before sampling at 1-second intervals, by an analogue-digital converter with punched paper tape output. A KDF 9 computer was used to calculate vertical turbulent fluxes of momentum, heat and moisture by eddy correlation, and also variances, power spectra and cross spectra using the fast Fourier Transform. Data were also copied onto IBM tapes which were processed on a 360/195 computer to yield graphical outputs of winds, temperature and humidity, and of instantaneous fluxes.

4. Results and discussion

(a) Introduction

Data summaries are given in Table 1. Sea-air temperature differences were obtained from conventional ship observations and in most cases were small so the estimated values for the surface heat fluxes are not very reliable. Additionally there was evidence for significant horizontal gradients of sea temperature in the vicinity of the ship at times and therefore listed surface fluxes may not be fully representative of the area-average values which are required if comparisons are made with observations obtained a few hundred metres above the surface. However on those occasions with balloon-borne observations at two heights and significant measured fluxes (runs 10-12) the common features are heat fluxes decreasing rapidly with height (in two cases changing sign) but moisture fluxes which on average show much less height variation. The boundary layer thickness, estimated from radio-sonde ascents, was 800m or more in these three cases (Table 2) and it is clear therefore that the buoyancy flux due to moisture was that primarily responsible for the observed cumulus development. Estimates for the buoyancy flux (≡ rate of production of turbulent kinetic energy due to buoyancy forces) at sensor height are given in the Table in the form of separate contributions from the heat and moisture fluxes. All the listed runs were in convective conditions with the sensors in the lower part of the boundary layer and it is interesting to note therefore that in a number of cases even at these modest heights of measurement the net buoyancy production was negative. The buoyancy flux would continue to decrease with increasing height up to cloud base and at first sight it is surprising that convection could exist at all in these latter cases above a few hundred metres. However as pointed out in § 1 it becomes less profitable to describe many of the features of the atmospheric boundary layer in purely statistical terms if moist convection is the dominant process and it is then necessary to seek explanations for the results such as are now being discussed by considering more specifically the non-random structure of the boundary layer.

Useful information on the organisation of the boundary layer in the sub-cloud region may be obtained by comparing the cospectra for heat and water fluxes. Figures 1 and 2 (taken from Thompson 1972) show unnormalised cospectra obtained at two heights in run 10 (plotted values above 0.1Hz are strongly affected by ship motion and are ignored in following discussions). At 45m although the net heat flux is positive there is a large negative contribution at low frequencies whereas the moisture flux is upward on all scales. The measurements at the upper level (140m) show contributions to the heat flux to be negative at most frequencies whereas the net moisture flux continues to be directed upwards though now with a negative component at low frequencies. There is evidence then for turbulent mixing on all scales producing a downward heat flux at 140m whereas only the largest scale eddies still transfer heat downwards at 45m. It is tempting to associate these large eddies with a generally sinking motion, presumably between clouds, and it is interesting to note how near to the surface this organised "turbulence" penetrates even in conditions of rather weak convection. In most respects then the variations of these cospectra with height are consistent with the ideas in § 1. The anomaly is the negative low frequency contribution to the moisture flux at the upper level and the consequent rapid decrease of the flux with height. If this is not due to sampling variations then it suggests that air within the convective layer's bounding inversion was moister than just below: this may well have been the case at the start of the run since a strato-cumulus layer at the inversion had dissipated only shortly before the run began. The results from the next observational period broadly parallel those of run 10, with the moisture flux's cospectral contributions at both heights positive at all frequencies whereas the heat flux contained a negative element at low frequencies which increased with increasing height. Run 12 was carried out a few hours later with a somewhat deeper boundary layer. Moisture cospectra were broadly similar at both heights, each showing a marked double peak. That at higher frequency occurred at approximately the same reduced frequency ($f = nz/\bar{U}$) at both levels, thus following the height scaling usually observed close to the surface, but low-frequency peaks were at roughly the same natural frequency suggesting an association in their case with deeper organised convection motions.

The decrease of heat flux with height was not accompanied in this run by increasing large low frequency negative contributions but the relative cospectral contributions at 185m (i.e. those normalised by the flux at measurement level) were algebraically smaller at low frequencies than at 90m, a variation with height similar to that found in the two previous runs.

(b) Entrainment across the top of the boundary layer

The boundary layer in runs 10-12 was shallow and therefore would be expected to adjust rapidly to turbulent transfers across its upper and lower boundaries. In these circumstances (ignoring flux divergence due to radiation) the variation of heat flux with height should be approximately linear. The observed vertical gradient of heat flux must be a function of the boundary layer thickness and the sensible heat flux at the surface (by analogy with dry convection) and also of the surface water vapour flux. The effectiveness of the vapour flux in promoting mixing across the capping inversion is strongly dependent on whether condensation with release of latent heat occurs. If there is condensation then the buoyancy flux in the upper part of the boundary layer is much enhanced and entrainment across the interface will be larger than could arise merely from buoyancy-induced mixing associated with the virtual heat flux. If it is assumed that the downward heat flux at the interface due to each unit of upward latent heat flux at the surface is a, and that due to each unit of surface sensible heat flux is b then the average gradient of vertical heat flux in the boundary layer is

$$\frac{\partial H}{\partial z} = -\left(H_0(1+b) + L_H E_0 a\right)/h \qquad (1)$$

where

H_0 = surface sensible heat flux
E_0 = surface water vapour flux
L_H = latent heat
h = depth of boundary layer

If the measured fluxes in run 12 are extrapolated to the surface it is found that $H_0 \sim 12\ \mathrm{Wm^{-2}}$ and $L_H E_0 \sim 47\ \mathrm{Wm^{-2}}$. Taking a rough value of 0.25 for b it follows from eq. (1) that

$$\frac{\partial H}{\partial z} \sim -5/95 = -(15 + 47a)/1100$$

or,

$$a \sim 0.9$$

Similar calculations for runs 10 and 11 using extrapolated surface heat fluxes and surface water vapour fluxes equal to those measured at 45m gave values for a of 1.4 in each case. In view of the assumptions underlying the calculations these estimates should be considered as having order of magnitude accuracy only, but they appear to give a clear indication that the magnitude of the surface water vapour flux was of overiding importance in determining the thermal structure of the boundary layer in these three runs. On the other hand they also suggest that even if all the surface flux of latent heat was released by condensation (which it was not) then this latent heat still entrains more effectively than a similar surface flux of sensible heat.

(c) Temperature and humidity correlations

In middle latitudes, in unstable conditions near the sea surface ($L = -50m$), Phelps and Pond (1971) found that spectral correlation coefficients for temperature and humidity were close to 1 over the reduced frequency range from 1 to less than 10^{-2}, with phase angles very close to zero (the spectral correlation coefficient is $S_{Tq}(n)/(S_{TT}(n)S_{qq}(n))^{1/2}$: here S_{Tq} is the temperature-humidity cospectrum and the S_{TT}, $S_{qq}(n)$ are spectral values). They explained the nearly perfect correlation as a consequence of the sea surface being the source of both temperature and humidity fluctuations. The present results are summarised in Table 3 and are in striking contrast. Here the largest measured correlations less than 0.4 over the range $10^{-2} < f < 1$. The measured upward sensible heat fluxes for these two runs was about 25 Wm^{-2} and thus was not insignificant: clearly then even in situations with relatively large upward fluxes of sensible as well as latent heat the effects of moist convection can dominate or at least strongly influence the turbulence structure down to quite near the sea surface.

(d) Detailed turbulence structure

It was pointed out in § 1 that in convective conditions a significant horizontal ordering of the sub-cloud turbulence structure is likely. Convection was shallow in the present cases where therefore this ordering might only be expected to any degree in the upper part of the sub-cloud layer, and nearer the surface the structure of turbulence might be anticipated to be dominated by relatively small-scale mixing processes initiated at the surface. In this context an inspection of turbulence records from JASIN is illuminating. In Figures 4 are plotted two sections of record obtain simultaneously at two heights in run 12, the parameters concerned being T, q and w (this last "eye-smoothed" from the original record). In Figure 4a (half way through the run) the temperature and humidity signals at 185m are in almost exact antiphase. The velocity trace shows long periods of downward motion interspersed with short sections with upward movement. The upward-moving air is generally moist but also relatively cool, suggesting an origin well above the surface in a region with potential temperature increasing with height up to sensor level. Downdraughts are dry and warm as expected, transferring heat downwards and moisture upwards. At 90m the overall pattern is again of T and q in antiphase but with short in-phase episodes in which both heat and moisture fluxes are upwards. Figure 4(b) (the start of the run) is in considerable contrast with nearly perfect correlation between T and q at 90m and fair correlation between these and w, implying a close coupling between surface and this level. Additionally the T and q records at 185m bear some resemblance to those at the lower level.

The cause of these marked variations of turbulence structure with time must remain speculative in the absence of further information such as all-sky cloud photographs and observations over a greater height range but it seems likely they are the result of changes in coupling between cloud and sub-cloud layers, perhaps depending on whether clear air or cumulus clouds are above the observing instruments.

5. Conclusions

Results from JASIN 70 have been used to demonstrate the importance of the vertical flux of moisture in maintaining shallow convection and controlling the structure of turbulence in the marine boundary layer. There is tentative evidence that the rate of warming of the boundary layer depends strongly on this vapour flux which appears to exert the predominant control on the rate of turbulent entrainment across the capping inversion. Temperature and humidity correlations display a markedly different behaviour from those nearer the surface and this and certain features from the turbulence records suggest that coupling between sub-cloud and cloud layers may at times extend down to near the surface even in weak convection.

References

Carson D J	1973	The development of a dry inversion-capped convectionally unstable boundary layer. Quart.J.R.Met.S. 99 pp 450-467.
Garstang M, Munday M, Sequin W R, Brown J D, La Seur, N E.	1971	Fluctuations in humidity, temperature and horizontal wind as measured by a sub-cloud tethered balloon system, IEEE Trans.Geosc., GE-9 pp 199-208
Readings C J, Golton E and Browning K A	1973	Fine scale structure and mixing within an inversion, Boundary-Layer Met.,
Lenschow D H	1970	Airplane measurements of planetary boundary layer structure, J.Appl.Met., 9, pp 874-884
Phelps G T and Pond S	1971	Spectra of the temperature and humidity fluctuations and of the fluxes of moisture and sensible heat in the marine boundary layer, J.Atmos.Sci., 28, pp 918-928
Thompson N	1969	Unpublished - Meteorological Office, Met O 14 Turbulence and Diffusion Note No.5.
Thompson N	1971	Turbulence and Diffusion Note No. 14.
Thompson N	1972	Turbulence measurements over the sea by a tethered balloon technique, Quart.J.R.Met.S. 98 pp 745-762
Thompson N	1973	An investigation of turbulence structure and fluxes over the sea by a tethered balloon technique, Unpublished Ph.D. Thesis, Imperial College, University of London.
Vasilchenko I V, Vorontsov P A Dovgalyuk Yu.S and Maslov S I	1962	Techniques and instruments for study of the planetary boundary layer from ships, Trudy Main Geophys Observatory, 135, pp 120-128
Yokoyama O, Hayashi M and Ogura Y	1969	Measurements of vertical profiles in the atmospheric surface layer up to 1000m high above the sea surface, Prel. Rep. of Hakuho Maru Cruise KH-69-3, pp 24-27, Ocean Res. Inst. Univ. Tokyo.

Table 1 General Data

Run No.	Date (June) 1970	Start (Z)	Length (Mins)	Inst Heights (m)	(1) Wind speeds 10m ($m s^{-1}$)	(2) Wind speeds at Inst ($m s^{-1}$)	(3) $\Delta\theta$ (^{o}C)	(3) Δq $x10^3$	(4) Estimated surface fluxes H_o $W m^{-2}$	(4) E_o $mg m^{-2} s^{-1}$	(4) τ $N m^{-2}$	(5) Measured fluxes H	(5) E	(5) τ	(6) L (m)
4	16	1127	100	90 185	2.6	4.5 4.4	-0.6	1.6	-2	5	-.009	-1 -1	9 0	-.010 .003	+55
5	16	1307	40	90 185	5.3	6.0 6.0	0	1.7	0	14	-.042	-4 -4	22 13	-.015 .016	-250
6	16	1914	104	90 185	2.3	2.7 2.8	-.0.1	1.0	-1	4	-.008	-3 -4	2 2	.006 .025	-130
7	16	2106	48	90 185	1	1 1	-0.1	1.0	0	2	-.002	0 0	0 0	-.003 .006	-30
8	17	1057	51	95	8.1	9.1	1.5	2.5	20	34	-.103	4	47	-.150	-80
9	17	1229	48	95	8.1	9.2	0.8	2.1	10	28	-.099	8	31	-.053	-130
10	17	1610	88	45 140	7.7	8.5 8.8	0.4	1.5	5	19	-.090	1 -8	20 6	-.080 -.059	-220
11	17	1749	93	45 140	6.9	7.6 8.1	0.4	1.9	5	21	-.073	7 -9	33 38	-.039 -.056	-145
12	17	2143	142	90 185	5.7	6.3 6.3	1.0	2.3	10	22	-.052	7 2	19 19	-.039 -.023	-55
13	18	1530	135	95	7.7	9.9	-0.6	1.8	-7	21	-.087	-4	15	-.045	+490
14	18	1745	60	95	8.5	10.6	-0.5	1.6	-7	21	-.106	4	53	-.064	+750
16	20	1021	86	95	7.3	8.3	0.3	3.4	4	41	-.081	-1	83	-.078	-150
17	20	1830	77	95	7.8	8.7	1.5	3.4	20	44	-.095	27	45	.005	-70
18	20	2005	92	95	8.1	9.0	1.7	2.8	23	37	-.103	25	44	-.013	-70

NOTES: Column (1) Estimated by downward extrapolation of tethered balloon data (at level nearest surface) using log profile corrected for stability

(2) Corrected for ship's speed.

(3) From Assman and bucket thermometer data on "Hecla"

(4) Using bulk aerodynamic formulae with $C_H, C_E, C_D = 1.3x10^{-3}$ in neutral conditions with corrections for non-neutral stability (Thompson 1971)

(5) From cospectra smoothed by eye to eliminate contributions due to ship motion

(6) Monin-Oboukov length calculated from ship observations (Thompson 1971)

Table 2 Boundary-layer depths, cloud data and buoyancy fluxes

Run No.	Instrument Height (m)	Boundary Layer depths (m)	Convective cloud data (amount, type, height (m))	Buoyancy fluxes $\times 10^4$ ($m^2 s^{-3}$) At surface (H)	At surface (E)	At sensor height (H)	At sensor height (E)
4	90	900	Nil	-.6	.2	-.3	.4
	185					-.3	0
5	90	900	Nil	0	.7	-1.1	1.1
	185					-1.1	.6
6	90	800	Nil	-.3	.2	-.9	.1
	185					-1.1	.1
7	90	800	Nil	0	.1	0	0
	185					0	0
8	95	650	5-8/8 St 300	5.7	1.7	1.1	2.3
9	95	700	3/8 Cu 500	2.9	1.4	2.2	1.5
10	45	800	3/8 Cu 450	1.4	.9	.3	1.0
	140					-2.2	.3
11	45	800	3/8 Cu 450	1.4	1.0	2.0	1.6
	140					-2.5	1.9
12	90	1100	3/8 Cu 550	2.9	1.1	2.0	.9
	185					.6	.9
13	95	1400	2/8 Cu 800	-2.0	1.0	-1.1	.7
14	95	1400	2/8 Cu 650	-2.0	1.0	1.1	2.6
16	95	1800	5/8 Cu 650	1.1	2.0	-.3	4.1
17	95	1600	4/8 Cu 650	5.7	2.2	7.7	2.2
18	95	1600	4/8 Cu 750	6.5	1.8	7.1	2.2

Table 3 Temperature and humidity correlations

Run No.	Instruments Heights (m)	Smoothed spectral correlations/phase angles (n ≤ 0.04) f =0.5	0.2	0.1	0.05	0.02	0.01
4	90	-.08/-180	-.14/-190	-.18/-190	-.24/-170	-.36/-190	-
	185	-.06/-160	-.19/-210	-.25/-200	-.17/-190	-	-
5	90	+.06/+70	+.08/-80	-.04/-140	-.24/-230	~ -.5/-180	-
	185	-.14/-170	-.22/-180	-.40/-170	-.50/-160	-	-
6	90	-.08/-180	-.09/-180	-.14/-170	-.36/-180	-.26/-180	-
	185	-.05/-160	-.08/-150	-.23/-180	-.23/-170	-.28/-170	-
7	90	-.18/-200	-.40/-190	-.46/-180	-.38/-190	-	-
	185	-.08/-180	-.08/-180	-.05/-200	-	-	-
8	95	+.09/+30	+.06/-10	0/-80	+.03/-10	-	-
9	95	+.20/+25	+.18/+25	+.18/+20	+.30/-10	-	-
10	45	-	+.10/+35	+.22/ 0	+.17/+10	+.18/-45	+.15/0
	145	-.01/-110	-.05/-200	-.15/-210	-.14/-210	-.06/-230	-
11	45	-	+.08/ 0	+.13/+30	+.16/ 0	+.05/-70	+.01/-80
	140	+.02/-70	+.03/-180	+.03/-40	-.02/-110	-.21/-150	-
12	90	+.08/+35	+.26/+10	+.32/ 0	+.35/+15	+25/+45	+.30/+10
	185	+.07/+50	+.13/+45	+.15/+15	+.07/+45	+.07/+40	-
13	95	-	-.04/-230	-.04/-250	-.09/-210	-.28/-170	-.34/-170
14	95	-	-.04/-210	-.18/-210	-.21/-200	0/-70	-
16	95	-	+.17/+10	+.04/-30	+.12/-30	+.06/-20	-.03/-120
17	95	-	+.19/ 0	+.25/+10	+.48/-20	+.52/-30	~ +.30/-30
18	95	-	+.20/+20	+.36/0	+.53/0	+.42/-10	+.08/0

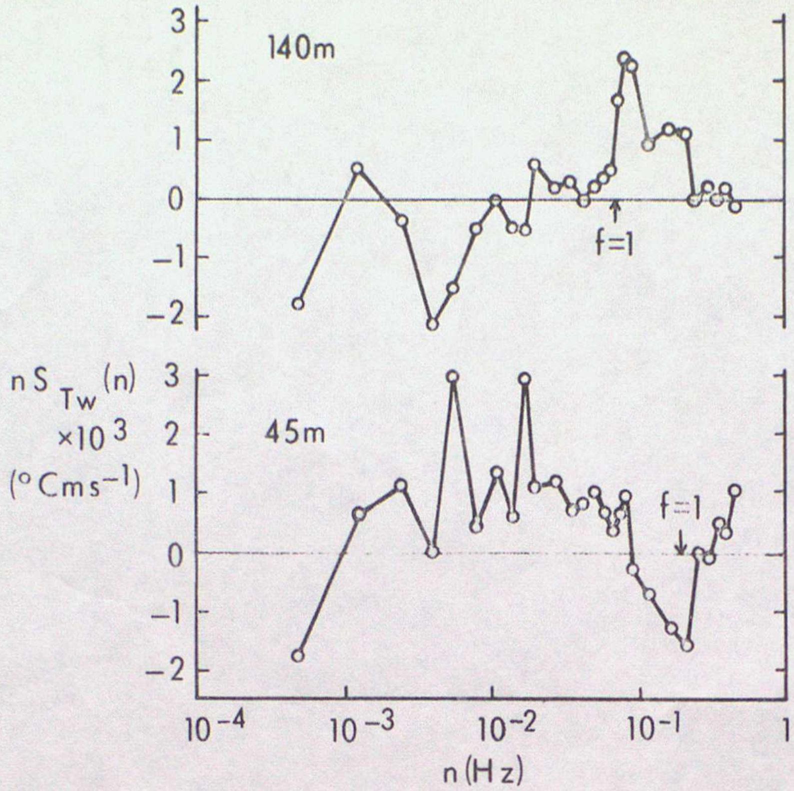

Figure 1 Tw Cospectra Run 10

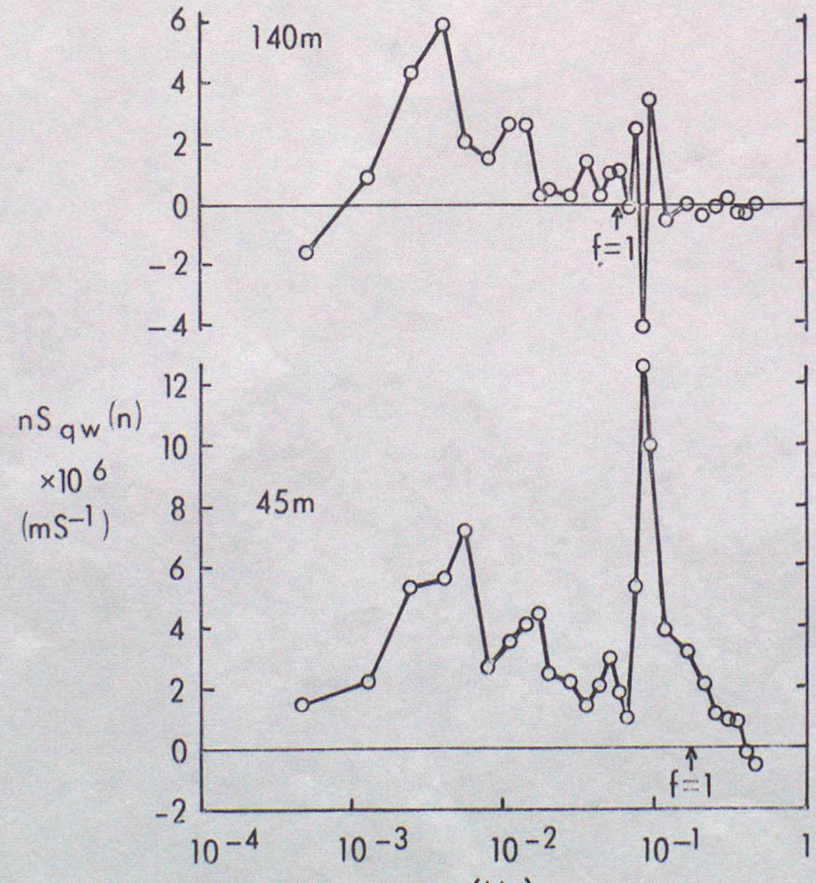

Figure 2 qw Cospectra Run 10

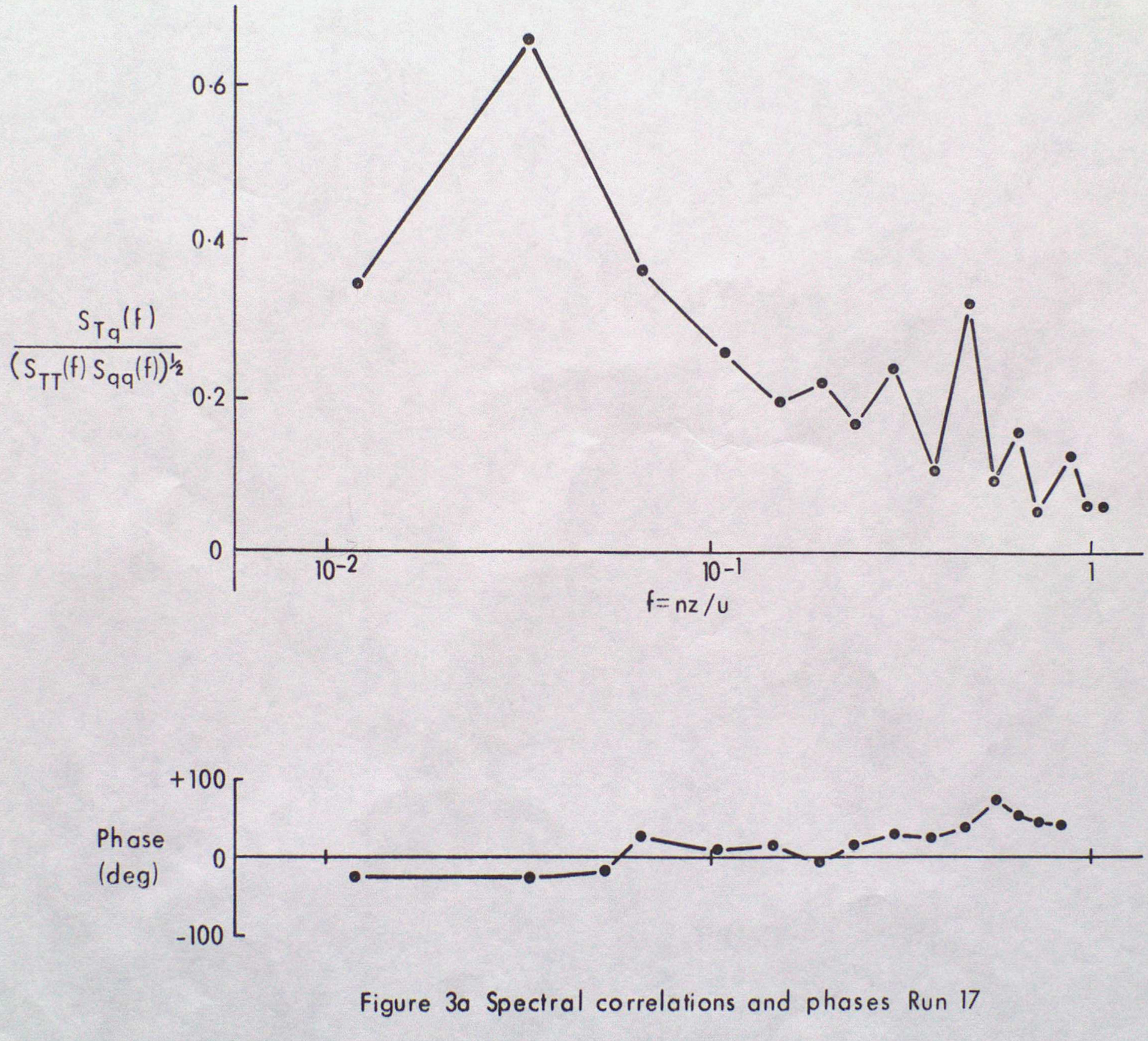

Figure 3a Spectral correlations and phases Run 17

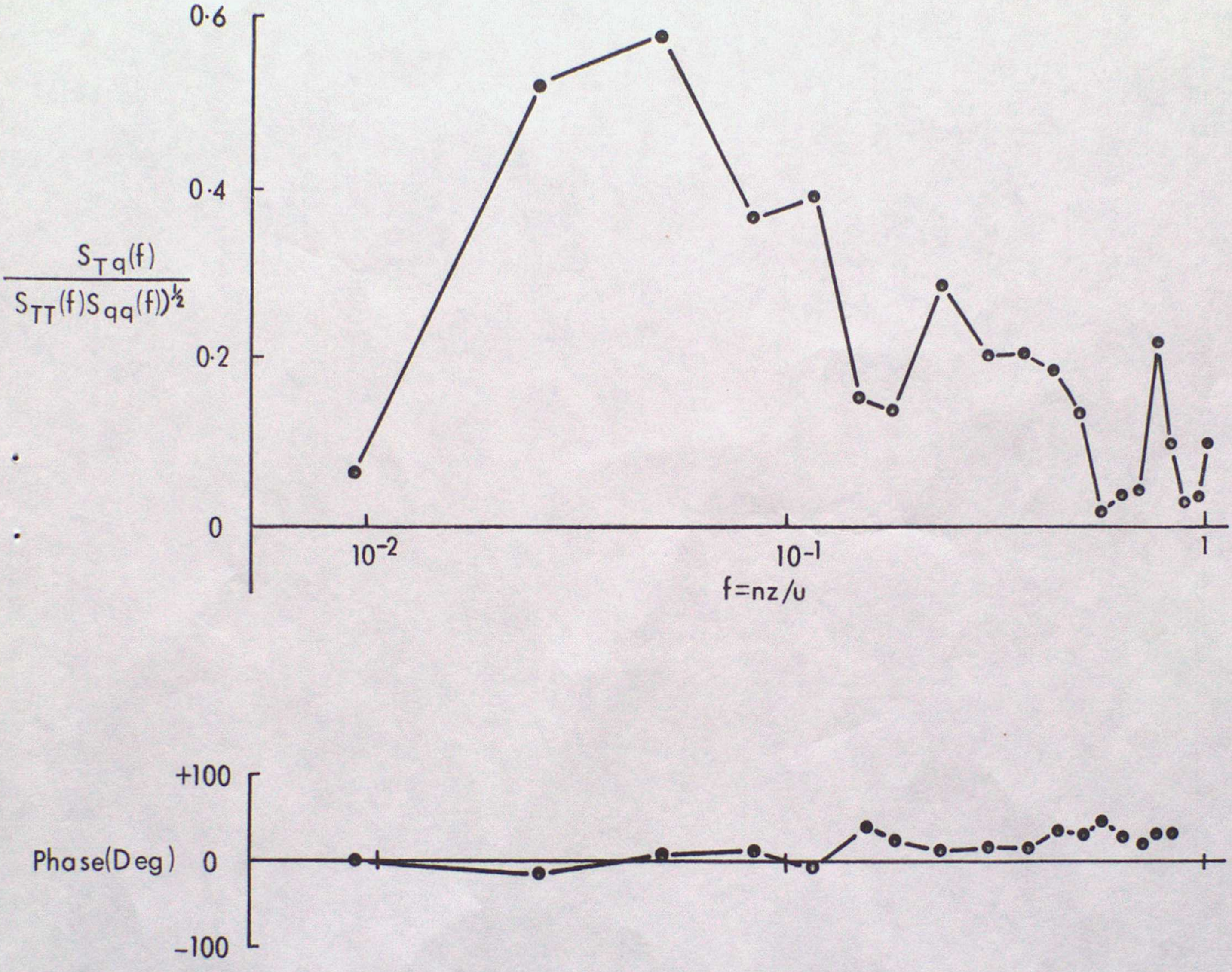

Figure 3(b) Spectral correlations and phases Run 18

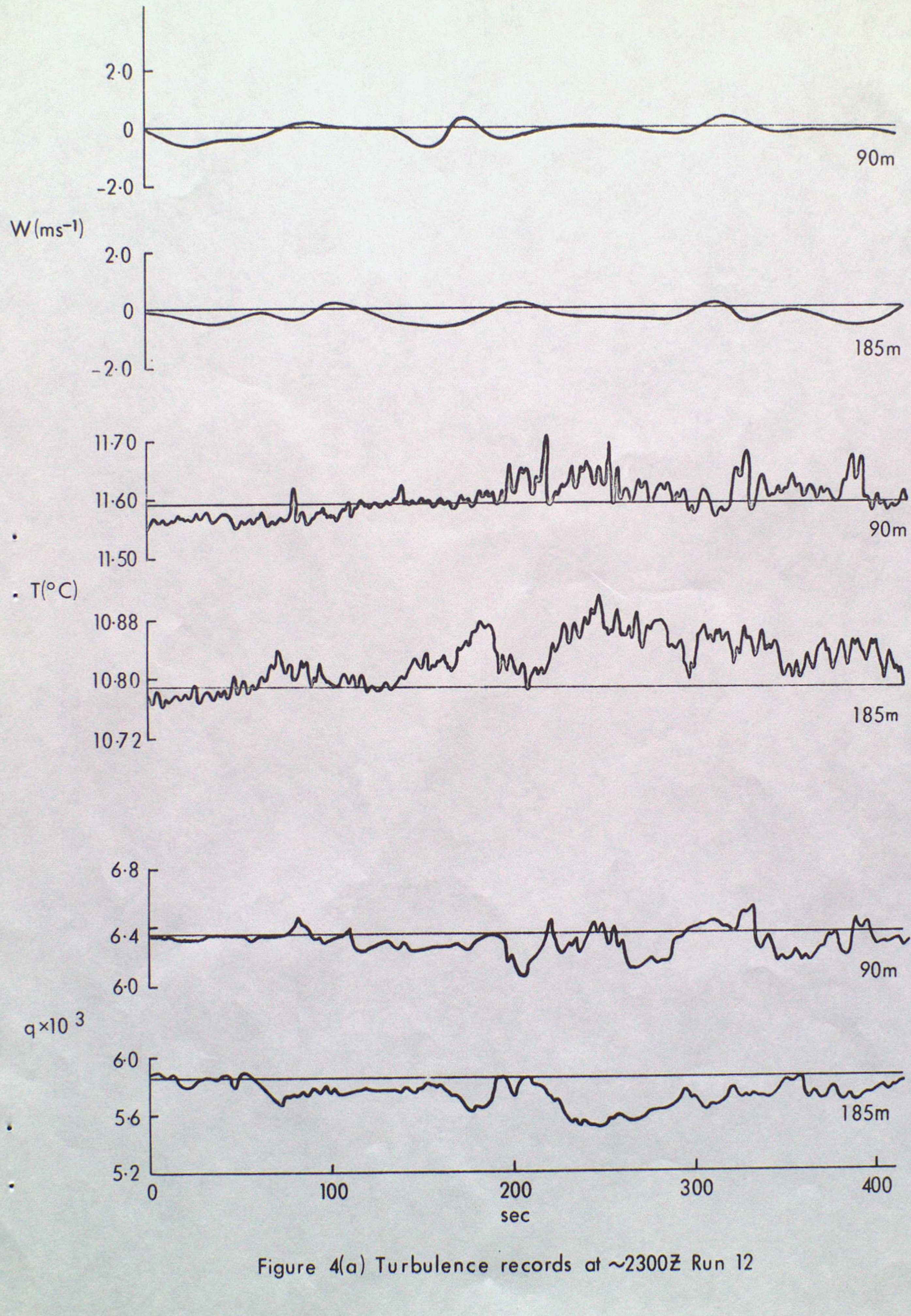

Figure 4(a) Turbulence records at ~2300Z Run 12

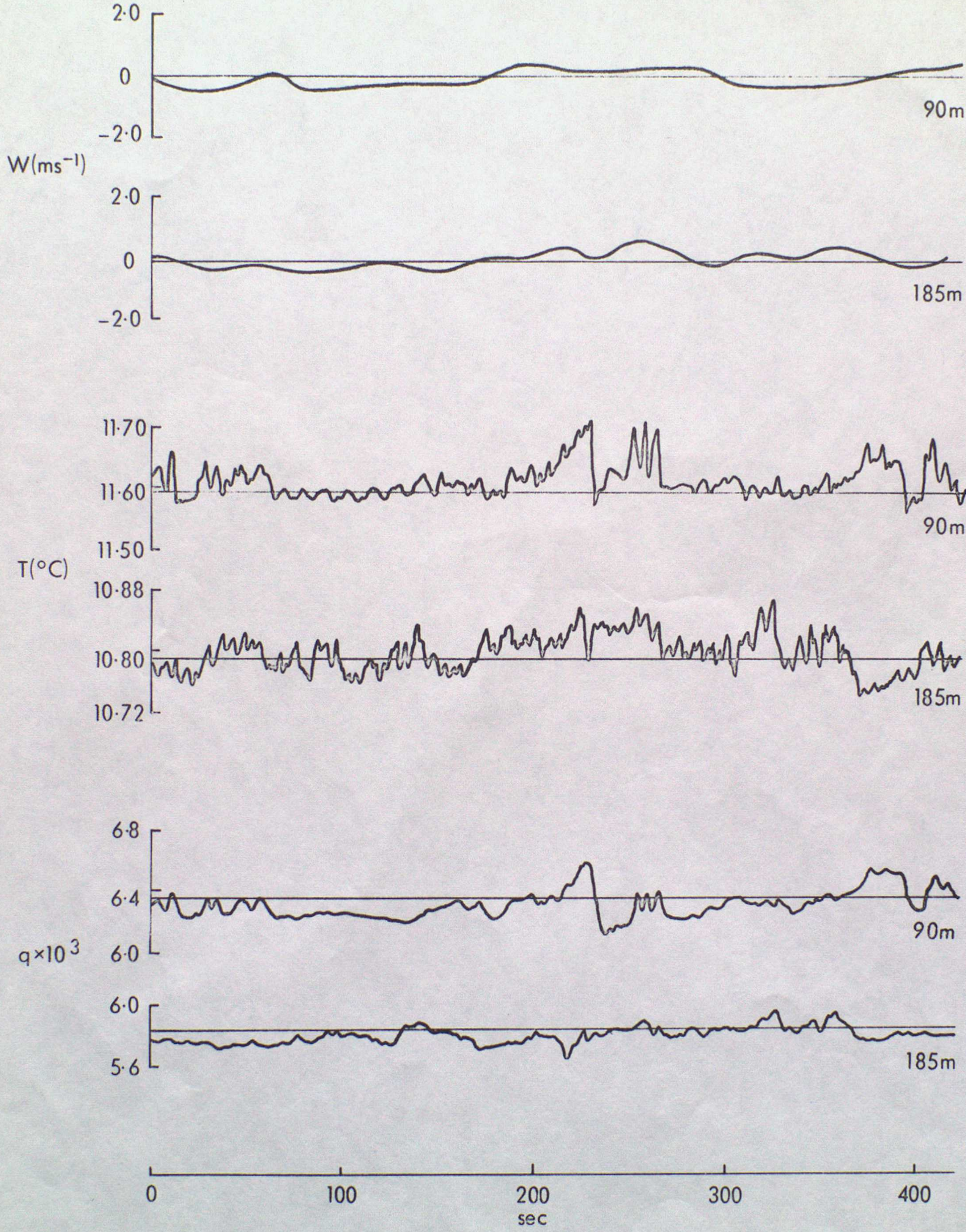

Figure 4(b) Turbulence records at ~2145Z Run 12