CORRELATED ENVIRONMENTAL CORRECTIONS IN TOPEX/POSEIDON, WITH A NOTE ON IONOSPHERIC ACCURACY.

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Submitted to
J. Geophysical Research
November 22, 1993

revised, May 20, 1994

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ABSTRACT.

Estimates of the effectiveness of an altimetric correction, and interpretation of sea level variability as a response to atmospheric forcing, both depend upon assuming that residual errors in altimetric corrections are uncorrelated among themselves and with residual sea level, or knowing the correlations. Not surprisingly, many corrections are highly correlated since they involve atmospheric properties and the ocean surface's response to them. The full corrections (including their geographically-varying time-mean values), show correlations between EM-bias (mostly the height of wind waves) and either atmospheric pressure or water vapor of -40%, and between atmospheric pressure and water vapor of 28%. In the more commonly used collinear differences (after removal of the geographically-varying time-mean), atmospheric pressure and wave height show a -30% correlation, atmospheric pressure and water vapor a -10% correlation, both pressure and water vapor a 7% correlation with residual sea level, and a bit surprisingly, ionospheric electron content and waveheight a 15% correlation. Only the ocean tide is totally uncorrelated with other corrections or residual sea level.

The effectiveness of three ionospheric corrections (TOPEX dual-frequency, a smoothed version of the TOPEX dual-frequency, and DORIS) is also evaluated in terms of their reduction in variance of residual sea level. Smooth (90-200

km alongtrack) versions of the dual-frequency altimeter ionosphere perform best both globally and within 20° in latitude from the Equator. The noise variance in the 1/sec TOPEX ionospheric samples is ~ (11mm)^2, about the same as noise in the Doris-based correction; however the latter has its error over scales of order 10^3 km. Within 20° of the Equator, the Doris-based correction adds (14mm)^2 to the residual sea level variance.

1 NTRODUCTI ON .

A common approach to assess the effectiveness of an altimetric correction is to measure the decrease in the variance of corrected sea level from the value for uncorrected sea level (e.g., Ray and Koblinski, 1991; Gaspar et al., 1994). The 'reduction in variance' criterion also underlies the estimation of coefficients relating some sea level signal believed to be proportional to an atmospheric or oceanic property; examples are the instantaneous, static ocean response to atmospheric pressure (VanDam and Wahr, 1993), and the altimetric 'electromagnetic bias' correction with wind and wave height (Fu and Glazman, 1991). All such estimates depend upon assuming that the altimetric corrections are uncorrelated among themselves and with altimetric residual sea level, or knowing the correlations.

Not surprisingly, several altimetric corrections are highly correlated among themselves, since they involve atmospheric properties or the ocean surface's instantaneous response to them. Furthermore, the uncertainties of corrections based on smooth fields, such as atmospheric pressure from atmospheric general circulation models, or ionospheric corrections based on models are correlated to the fields themselves: where the spatial or temporal gradients of the true fields are steepest, the uncertainties of the models are largest. As a consequence, residual sea level measured

wi t h al t imet ry c ont ai ns some e rrors whi ch are p r oport i ona .] t o a t m osp h eri c f ields and t o ot her al t imet ric c o rrect i ons .

Th e purpose of t hi s paper i s t wof ol d: 1) t o document t he correl at i ons among t he ma in al t imet ri c correct i ons in Topex/P osei don and t. o di scuss som e c on sequences; 2) t.o assess t he a c cura cy of the Dori S i onospheri C c orrect i on .

The TOPEX/POSEI DONsat ell i t e carri c's t wo al t imet ers. One is a dual - f requency al t imet er (1.3. 6 GHz anti 5.3 GHz, Cal l ahan, 1 993) t hat m ea sur es t he t ot al el ect ron cont ent along the alt imet er pulse's path. This al timet er 3's on approximat ely 90% of t he t ime . The el ect ron densi t y causes t ime del ays 011 t he pul se t hat would t ranslat e as errors in sea level, t he quant ity of int erest, unless corrected for (~2. 18 mm per lx] 0^{16} ele ctrons/m^2 at 13. 6 GHz, Lorell et al, 1982) . The correct ion has a mean val ue of ˙43 mm and a st andard deviat ion of - 29 mm; wi thin 20º of the Equat or, both t he mean (63 mm) ant] t he variability (40 mm) are higher. The correct i on is maximum around 3 PM 1 ocal t ime (see Ri sbet h and Garriot, 1969; Callahan, 1984; Chel ton, 1988) .

About 10% of the t ime, t he light er, low power, single-frequency solid-st at e al timeter ('Pose idon ') is used, and the i on o sph e ri c co r rect i on must be obt ained f rom anot her source. The sat el] i te al so c arri es a Doppl er recei ver cal l ed DORI S, wh os e m a i n p u rp os e is t o const rain t he comput ed posi ti on of the satellit e, in conjunct i on wi h a l arge number of ground st at ions. DORI S al so me asures in t wo carrier f requencies (0. 4 a n d 2 GH z, Fleury et al ., 1 991) o correct for i onospheri c del ays t o i ts signal, hut t he pa hs bet ween t he sate!.)].it e and DORIS ground st at i ons ?] J-C! usually slant ed off the vert i cal , where the al timet er's pat h 1 ies. These slant pat h del ay s are used t ogether wi t. h an i onosphe ri c model (Bent) to est ima t. e t he vert ical path delay.

Bot h Geosat (Ch eney et al ., 1 989) and the current ER - 1 sat ellit e have only single f requency a] timet er, and must

rely on a model ionosphere to correct for this effect. Musman et al. (1990) concluded that residual ionospheric errors would be removed when applying orbit corrections t. o i. he Geosat data, except possibly during geomagnetic storms. Geosat had between 30 cm and 100 cm orbit error, depending on the orbit used ant] the date (Zlotnicki et al., 1 99.3) and all orbit error removal schemes a 1 so absorbed significant energy in oceanic motions that could riot t hus be recovered. This approach is not acceptable for TOPEX/ POSEIDON, whose orbit error is below 5 cm (Morris and Gil 1, 1994) and whose goal is to recover the larger scales of the ocean circulation (Fu et al., 1994).

The design and cost of future altimetric missions are also affected by knowing whether a single frequency altimeter with a DORIS-derived ionosphere can perform as well as a dual-frequency altimeter. Hence, the second purpose of this paper.

DATA.

The data used are "from the AVISO Merged Geophysical Data Records ('AVISO MGDR', AVISO, 1993), containing data from hot h the TOPEX dual-frequency and the POSEIDON solid-state altimeter. Only data from the TOPEX dual-frequency altimeter (shout. 90% of the time) were used in this study, i 11 order to have both main ionospheric corrections available. The time coverage is about 326 days starting January 11, 19.9.3 (Topex cycles 12 through 44). The spatial coverage are the global oceans up t. o 66° of latitude, except where an equatorial band is discussed.

Y'tic: sea level residuals were computed in three steps. First, for each record in the AVISO MGDR a sea level height above the mean sea surface was obtained as:

H_Sl = H_Sat - H_Alt - EMB_K2 - Iono_T - Dry - Wet_Rad -

$$OTideCR - STide - PTide - InvBar - OSU_MSS \quad (1)$$

where H Sat is the satellite height from the NASA orbit., H A.? t is the altimeter range! corrected for instrumental effects, EMB K2 is the electromagnetic bias correction with the NASA algorithm, 1 ono T is the ionospheric correction from the dual - frequency altimeter, Dry is the dry tropospheric correction from the French Meteorological Office, Wet_Rad is the wet tropospheric correction from the TOPEX microwave radiometer, OTide CR is the ocean tide estimate (Cartwright and Ray, 1991, model), STide is the solid Earth tide estimate, PTide is the pole tide, InvBar is the inverted barometer effect, and OSU MSS is the Ohio State University mean sea surface height (Rapp et a]. , 1 991; Basic and Rapp, 1992). All corrections are included in the AVISO MGDR.

The second step involvedediting out spurious data: records were not used when the flags alt bad 1 or alt bad 2 had any bit. on, when the current mode 1 flag was not set to 'Fine Track' or showed problems (bits 4-5), when any term in (1) had a default (missing) value, or when |H Sl. | > 3000 mm (some of these criteria do not apply to the Pose:.idon altimeter).

The third step involved interpolating H_Sl. to a fixed set of longitudes (relative to the Equator crossing longitude) using an exact cubic spline alongtrack, to allow collinear differences. Finally, at each latitude φ, longitude λ, time t., the mean sea level over the time span studied was removed:

$$H_res(\varphi,\lambda,t) = H_SL(\varphi,\lambda,t) - \frac{1}{n}\sum_{i=1}^{n} H_SL(\varphi,\lambda,t_i) \quad (2)$$

METHOD

The main indicator of quality of a correction used here is the reduction in variance of residual sea level after applying the correct. ion. The details of this criterion arc!

discussed here, since the presence of correlations among the corrections affects the interpretation.

Let h be the truesea levelheight at someplace and time, and let h' be a measurement of h that requires an additive correction term whose true value is c. Think of c as any of the environmental corrections (wet troposphere, ionosphere, etc); think of h as sea level perfectly corrected for everything other than c.

$$h' = h + c \tag{3}$$

Let c' be a measurement of c, that includes a random error term e

$$c' = c + e \tag{4}$$

Then, h will be estimated as:

$$h'' = h' - c' \tag{5}$$

Let $<hh>$ denote the expected value of $|h|^2$, i.e., the variance of h, and similarly with the other quantities (assume $<h> = <c> = \ldots = 0$). Then Q, defined as:

$$Q = \frac{(<h''h''> - <h'h'>)}{<c'c'>} \tag{6}$$

measures how the variance of the observed h' has changed after applying the estimate c' of the correction c. For example, $Q = -1$ means that applying the correction has decreased the variance of corrected sea level from the uncorrected variance, and that the decrease in variance exactly equals the variance of the correction. From (3) through (5) it follows that Q is:

$$Q = \frac{-<cc> + <ee> - 2<hc> - 2<he>}{<cc> + <ee> + 2<ce>} \tag{7}$$

If $<hc> = <he> = <ce> = 0$ then $Q = \frac{-<cc> + <ee>}{<cc> + <ee>}$ (8)

so, when no correlations exist among the various terms, the quantity Q varies between -1 and +1. Only in the absence of correlations the following interpretation is warranted: $Q \to -1$ when the error of the correction is negligible ($\langle ee \rangle \ll \langle cc \rangle$), and $Q \to +1$ when the error of the correction totally dominates the estimate c'. In the absence of correlations, a correction can be called more 'efficient' if its Q is closer to -1, and a correction estimate can be called more 'useful' if it decreases variance more than a competing estimate.

Conversely, absolute values of Q larger than 1 are sufficient proof that correlations among the various terms exist; in such a case the increase or decrease in variance between uncorrected and corrected sea level may exceed the variance of the correction applied. Furthermore, in that case, the fact that a correction decreases the variance of residual sea level is not proof that the correction is useful.

Notice that it was assumed that h itself had no errors other than c, to simplify the algebra. In fact, h is the result of a measurement and contains measurement errors. The term $\langle hc \rangle$ in eq. (7) therefore includes not only correlations between the current correction (think of the wet tropospheric correction) and sea level, but also between the current correction and residual errors in sea level after applying other corrections (for example, the dry tropospheric term).

CORRELATIONS AMONG CORRECTIONS.

Table 1 gives an idea of the relative size of selected corrections, by listing, in decreasing order, their standard deviation (σ) for TOPEX/POSEIDON. The 'full' σ was computed from the full correction: it includes energy in its geographic variability as well as in its time variability;

the 'collinear' σ was computed after subtracting at each latitude - longitude point the local time average value of the correction. The 'full' σ is relevant to studies of absolute dynamic topography above! the geoid; the 'collinear' σ is relevant to studies of time-varying ocean motions, where the local time average that is removed includes the geoid and the averages of all the Corrections.

The ocean tide correction is the only one with more energy than residual sea level (see Schrama and Ray, 1994; Knudsen, 1994; Wagner and Cheney, 1992), which explains why small uncertainties in the tides cause large errors in the studies of other sea level signals. The inverted barometer term is the second most, energetic correction. Neither tides nor inverted barometer are 'corrections' in the sense of modifying altimeter measurements to yield the correct sea level, but. are attempts at. modeling and removing 'known' ocean signals to study the rest (see Tai, 1993). The 'corrected sea level' in the 'full values' columns contains an uncorrected error due to uncertainties in the Ohio State mean sea surface when equation (1) is used: there is a 400 mm bias and a 240 mm offset between the centers of mass of the TOPEX sea level and the mean sea surface (Callahan, 1993), plus a residual error in the mean sea surface that. Knudsen (1994) estimated at 75 mm rms, much of it concentrated in the western equatorial Pacific and Indian oceans.

Table 2 lists the global correlations found among the values of selected corrections and sea level, both for full values and collinear differences. These were computed as simple correlations for any two variables as if the other ones did not exist., rather than as a multiple regression. Correlations of 1 % or higher are different from zero with 99% confidence, conservatively assuming that. points separated by at least- 10° in latitude and longitude, and 1/2 day are independent (about 196,000 degrees of freedom in the 11.8

mi 11 i on 1 -second sampl es used) . The dry tropospheri c correction is not listed, since it is very close to 4.4 times the invert ed baromet er, pl us a gl obal ly averaged val ue.

How do these correlat ions arise? Consider first the simple st., corrections proportional to atmospheric pressure (inverted barometer) and water vapor. Over the range of lat i tudes covered by Topex/Poseidon, 66°S to 66°N, the temporal mean values of both are higher at. low latitudes (e. g. , Figure 1) , even though if the sampling continued to polar latitudes, pressure would increase again, associated with sinking air, while water vapor would not (see Wallace and Hobbs, 1977; Battan, 1974) . This helps understand the large (28%) correlation on full val ues. The temporal variabil i ty of atmospheric surface pressure is larger at high latitudes while that of water vapor is larger at low latitudes (see Figure 1a, b) , a fact that decreases any correlation on the temporal variabil i ty. However, near the Equator, low atmospheric pressure and high evaporation are tied to the Intertropical Convergence Zone, whose mot i on shifts both the patterns of pressure and water vapor, leading to the -10% correlation on the time variations at fixed geographic positions.

The correlation between EM bias and pressure is due to the high waves and pressure variability in subpolar lat. itudes, since EM bias is, to first order, a small percentage of the significant. wave height (S WH), some of it 'seas', locally generated by the wind and related to local atmospheric pressure, and the rest 'Swell ', generated elsewhere. Notice that this correlation is almost as important on the full corrections (41%) as on their time variations (30%) . The sensitivity of estimated EM bias coefficients to the invert ed barometer correction was emphasized by Gaspar et al . (1 994) and Rodriguez (1 994) .

The high correlation (37%) between full values of i onospheric electron content and tropospheric water vapor is

the result- of t-he increase of the mean of both fields towards low latitudes (Figures 1a, c) , and is considerably weakened (5%) once their time variations alone are considered. TOPEX/POSEIDON samples a very narrow range of 1 oca l times at any fixed latitude in any one 10 day cycle (Figure 2), and the local times of Equator crossing are the most. frequently occurring in the global data set. . Therefore, the satellite maps latitudinal variations into apparent local-time variations. This causes the peculiarity that, when viewed by Topex/Poseidon, water vapor is a strong function of local time: both ionosphere c elect.ron content (fig. 2c) and water vapor (fig. 2d) peak at the local times of Equator crossing; one can still distinguish the ionospheric plot since electron density is much higher during local daytime.

The relatively large correlation between wet troposphere c correction and residual sea level (-20%) is mostly due to a water vapor error in the OSU MSS, which is based on the Geosat data with the Fleet Numerical Ocean Center (FNOC) water vapor (Yi, 1992; Knudsen, 1994) .

Th c -11% correlation between ionospheric electron content and EM-bias in collinear differences is harder to understand. EM-bias is essentially proportional to SWH, but the correlation between ionosphere and SWH is stronger: 15% in the collinear differences. Some possible explanations can be exe] uded. The correlation between EM-bias and the Doris ionosphere is -9%, so most of the -11% is not the instrumental effect described in Imel (1 994; see his figure 5) , whereby corrections to the Topex altimeter's Ku and C band ranges are themselves functions of SWH, and those: two apparent ranges are used to compute the ionospheric correction. Neither is there a significant difference when the correlations bet. ween ionosphere and SWH are computed using the K-band SWH or the C-band SWH, excluding other instrumental reasons (Imel, 1 994) . The correlation with EM-bias is much stronger (-1 6%) poleward of 40°S, where SWH is

strongest., than wit hin 25° of the Equator (–8%), and an expl oratory search through the Topex data shows a weak diurnal cycle (viewed in small geographic areas) to the SWH. Any consistent diurnal cycle in SWH would generate a strong correlation with the ionosphere. While several physical reasons can be invoked to justify a diurnal cycle in waveheight (diurnal cycles in the wind or in the nc!ar-surface stratification), this issue deserves a more careful discussion, outside the scope of this paper.

These correlations can cause a problem. If the fields needed for the corrections were perfectly known, and if there were no doubt. what-ever as to the formula for t-he correction, then the correlations would be harmless. However, consider the inverted barometer correction. The pressure field used is the result. of a numerical model of the atmosphere (European Center for Medium Range Weather Forecast, modified by French Meteorological Office), updated with data assimilation, a good but imperfect model, with larger uncertainties in areas with no data. This field is used for the dry tropospheric correction, whose formula is not. in doubt, and also for the inverted barometer correction. The latter is the complete oceanic response to pressure in a specific range of space and time scales (Wunsch, 1972), and outside that range there are additional oceanic motions in response to atmospheric pressure (Ponte et al., 1991). Since the correction is applied with no regard to space or time scales, there is bound to be a pressure-related residual term in residual sea level . When t-he corrections used are smooth versions of the true values and based on sparse data, as is the case with atmospheric pressure data, their residual errors are usually correlated with the corrections themselves: atmosphere c pressure uncertainties are higher in the area of the Antarctic Circumpolar Current (Strub, 1988) due both to the large variability of pressure and low dens.ity of observations. ionospheric electron content from Doris, which

involves a space-time interpolation among slant paths between the satellite and fixed ground stations, should have larger errors near the Equator, where the large electron content variability may not be sampled rapidly enough or closely enough. On the other hand, there is no particular reason for the residual errors in the TOPEX ionospheric measurement or the TOPEX Microwave! Radiometer water vapor to be correlated with the signals themselves.

DISCUSSION and CONCLUSIONS.

Table 3 shows the reduction in variance Q (equation 6) of corrected sea level, both with collinear differences and full values, obtained by applying certain corrections. Of course, to minimize the effect of correlations among correct-ions, all corrections except the one being discussed are applied to the data. While the author was unable to derive analytically a confidence interval on the statistic Q, he computed Q from both a small subset. and the full data set. with the following result: the global Q based on only 1.2×10^6 points differed from the Q based on 11.9×10^6 points with a median absolute value of Q of 0.04, and a maximum difference of 0.22; for the equatorial subset, with 0 .35x106 vs 3.3×10^6 points, the median Q difference was 0.15 and the maximum 0.16. So, differences in global. Q of at least, 0.1 appear significant; for the equatorial subset, 0.16 is a significant. difference.

Consider first the ocean tide correction (Cartwright and Ray), since its interpretation is simplest. It is very energetic, and its application removes 103% of the variance in the correction, which is within 3% of a perfectly efficient correction (note that two corrections for the same effect can both decrease variance by 100% of the corrections' variances, but the one yielding the lower residual sea level variance will be the better one, in the absence of correlations) . This effect is the same for collinear or full

values of the ocean tides Since the tides arc decorrelated from everything else, t-he Q can be int erpreted as in equation 8.

Now consider the wet tropospheric term. When using full corrections, its Q is only 0.03, suggesting that it is a useless correction. However, Table .? shows that the full wet. tropospheric term is correlated to EM bias, ionosphere, inverted barometer and residual sea level . Therefore, by equation (7) , no interpretation can be assigned to this Q unless we quantify the error in theother terms, mostly the OSU MSS. The wet tropospheric correction for collinear differences shows a Q of -0.65 (only 65% of the variance in the correction goes to reduce sea level variance) . l-n the absence of correlations this would suggest. a good but imperfect correction, but Table 2 hints at another explanation: atmospheric pressure and water vapor are correlated, and the inverted barometer correction is imperfect (Fu and Pihos, 1994), hence there is a residual component of sea level tied to a local, instantaneous response to atmospheric pressure, which also correlates with the wet tropospheric term. In addition, any residual errors in the EM bias will also affect the Q for the wet tropospheric correction, due to their correlation.

The dry tropospheric row of Table 3 is further proof that the inverted barometer assumption fails over some parts of the ocean some of the time, or the pressure field used is inaccurate, or both. If the dry tropospheric correction is applied after the inverted barometer (consider collinear differences only), only 7% of its variance goes to reduce sea level variance, leaving 93% of its variance as a pressure-related signal in residual sea level . If no inverted barometer is applied, applying a dry tropospheric termwith (19 mm)^2 variance reduces the variance of sea level by a huge 8.96 x (19 mm)^2. Inverted barometer and dry tropospheric terms, while physically very different (Chelton, 1988; Tai,

1992) are essentially proportional to the same atmospheric pressure, but inverted barometer is over 4.4 times larger with a weak latitudinal variation due to gravitational changes (Callahan, 1993).

The inverted barometer effect on the EM bias term (Fu and Glazman, 1991; Rodriguez) is almost as striking: if one does not. apply the inverted barometer term, any EM bias correction will increase sea level variance. As corollary, any uncertainties in the pressure data or inverted barometer response of the ocean will severely affect estimates of the EM bias coefficients (see Rodriguez and Martin, 1994), and coefficients computed with one correction will need to be re-evaluated if the inverted barometer correction is changed.

The collinear cl-inferences of ionospheric corrections show a clear pattern, globally or within 20º of the Equator. The smooth version (90 km alongtrack average) of the TOPEX dual-frequency altimeter is the best correction, removing (11 mm)^2 more variance than the unsoothed version or the Doris correction, globally. These numbers can be interpreted also as the accuracy gains in using one correction instead of the other. These values are consistent with Morris and Gill's (1994) estimate of 9 mm in the Great Lakes area, where there is no significant oceanographic signal. Within 20º of the Equator, the smooth TOPEX correction removes (14 mm)^2 more variance than the Doris estimate. No significant difference in the results is obtained by smoothing the TOPEX correction over 200 km alongtrack (see also Imel, 1994) . The correlation between ionospheric and EM-bias terms means that uncertainties in the latter will affect this conclusion to some extent.

The variance numbers mask a difference in length scales and the concentration of the Doris ionospheric error at low latitudes: as illustrated in figures 3, the difference between smooth and unsmooth TOPEX ionospheric estimate is uncorrelated 1 second noise', but the difference with the

Doris-based correction occurs over much longer spatial scales. As shown in Figure 4, a consistent, apparent, sea level difference of 3 cm across the equatorial Atlantic or a 2 cm difference around 20°N across the whole Pacific can be produced simply by the difference between Topex and Doris ionospheric terms. Features of this nature must be kept in mind when interpreting sea level differences among cycles with different. ionospheric corrections.

ACKNOWLEDGEMENTS .

Akiko Hayashi expertly programmed and carried out all the gridding, editing and data management.. Terence Chow programmed an early version of these calculations. Discussions wit-h David Imel and Ichiro Fukumori, and detailed comments by two reviewers were very helpful. This work was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration, and was funded by the TOPEX/POSEIDON Project.

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FIGURE CAI'~'1 ON S

Figure 1 . Zonal averages and standard deviations (drawn as error bars) of corrections as a function of latitude. DRY : dry tropospheric, WET: wet tropospheric from radiometer, 10NO : Topex dual-frequency ionospheric, EMB: EM bias, NASA algorithm.

Figure 2. All functions of local time, for a 5 day period (the second half of TOPEX/POSEIDON's cycle 19):
(a) latitude sampled
(b) histogram of local times
(c) ionospheric correction
(d) wet tropospheric correct.ic)n.

Figure 3. Ionospheric corrections f-or one particular daytime pass of TOPEX/POSEIDON: descending pass 210 (equator crossing=-162 .28º, on day 38 of 1993.

Figure 4. Apparent sea level difference, in mm, between two cycles (see label above maps) , caused solely by the difference between Topex and. Doris ionospheric corrections. The maps were obtained by gridding over 10 days and 5º the ionospheric differences, then subtracting the two 10 day maps. This simple gridding, comparable to more sophisticated ones an oceanographer might_ use to study large scales, combines both the large daytime and small nighttime ionospheric values.

TABLE 1.

CORRECTION	coll.diff.		full values		
	σ(mm)	σ(%)	σ (mm)	σ(%)	mean (mm)
ocean tide (C&R)	305	282	307	135	0
corrected sea level	108	100	228	100	--
inv. barometer	84	118	134	59	0
wet. tropo (rad)	47	44	90	39	14
em bias (TOPEX)	29	27	38	17	67
i ono (TOPEX)	29	27	33	14	43
dry tropo (FMO)	19	18	32	14	2299

Standard deviation (σ) and mean values of residual sea level and various corrections, in mm and as a percentage of the sd of corrected sea level. Columns labelled 'full values' refer to the full values of the corrections and to sea level above the OSU mean sea surface (eq. 1). Columns labelled 'coil.diff.' refer to collinear differences of both sea level and corrections, as in equation (2), with zero mean value at every latitude-longitude point.

TABLE 2.

	hh	ib	wet	ot	emb	io
hh	--	47	**-7**	3	**-1**	-1
ib	-3	--	-10	0	-30	0
wet	-20	28	--	0	-12	5
ot	1	0	0	--	0	0
emb	3	-41	-46	0	--	-11
io	-5	13	37	0	-30	--

Correlation coefficients (in %) among corrections and residual sea level 'hh'. Upper diagonal (bold) : collinear differences. Lower diagonal : full values of correction, or sea level above the OSU MSS.

ib: inverted barometer

wet : from the radiometer

ot : Cartwright and Ray ocean tide

emb: EM bias, NASA algorithm.

io: ionospheric, from Topex altimeter.

COLLINEAR DIFF.				FULL VALUES		
Q	rms (corr)	rms (h)		Q	rms (corr)	rms (h)
			GLOBAL, ALL CORR APPLIED			
-1.03	305	108..?	Ocean Tide (C&R)	-1.03	307	.?28.3
-0.65	47	108.2	Wet Tropo (rad)	0.03	90	2.28.3
-0.07	19	108.2	Dry Tropo	-0.31	32	228.3
-0.79	84	108..2	Inverted Barometer	-0.89	134	228.3
-0.89	.29	108.2	EM Bias (Topex)	-1.41	38	228.3
-0.90	29	108.2	Iono TOPEX (global)	-0.24	33	228.3
-1.10	28	107.7	Tono TOPEX smooth (global,	-0.42	32	.?.27.9
-0.95	28	108.3	1 ono Doris (global)	-0.3.2	31	228.2
			EQUATORIAL ALL CORR APPL			
-0.95	41	91.3	1 on o TOPEX equatorial	-1.16	4.?	248.1
-1.02	40	91.3	1 on o TOPEX smooth equat.	-1.31	41	248.1
-0.80	41	91.3	Iono Doris equatorial	-1 .1.?	43	.?48.1
			GLOBAL, INVBAR NOT APPLIED			
-0.27	47	131.9	Wet Tropo (rad)	-0.81	90	.261.0
-8.96	19	131.9	Dry Tropo	-8.66	32	261.0
0.91	29	131.9	EM Bias (Topex)	1.50	38	261.0

Q: computed from equation (6)

σ_{corr}: standard deviation of the correction, in mm.

σ_h: standard deviation of corrected sea level, in mm.

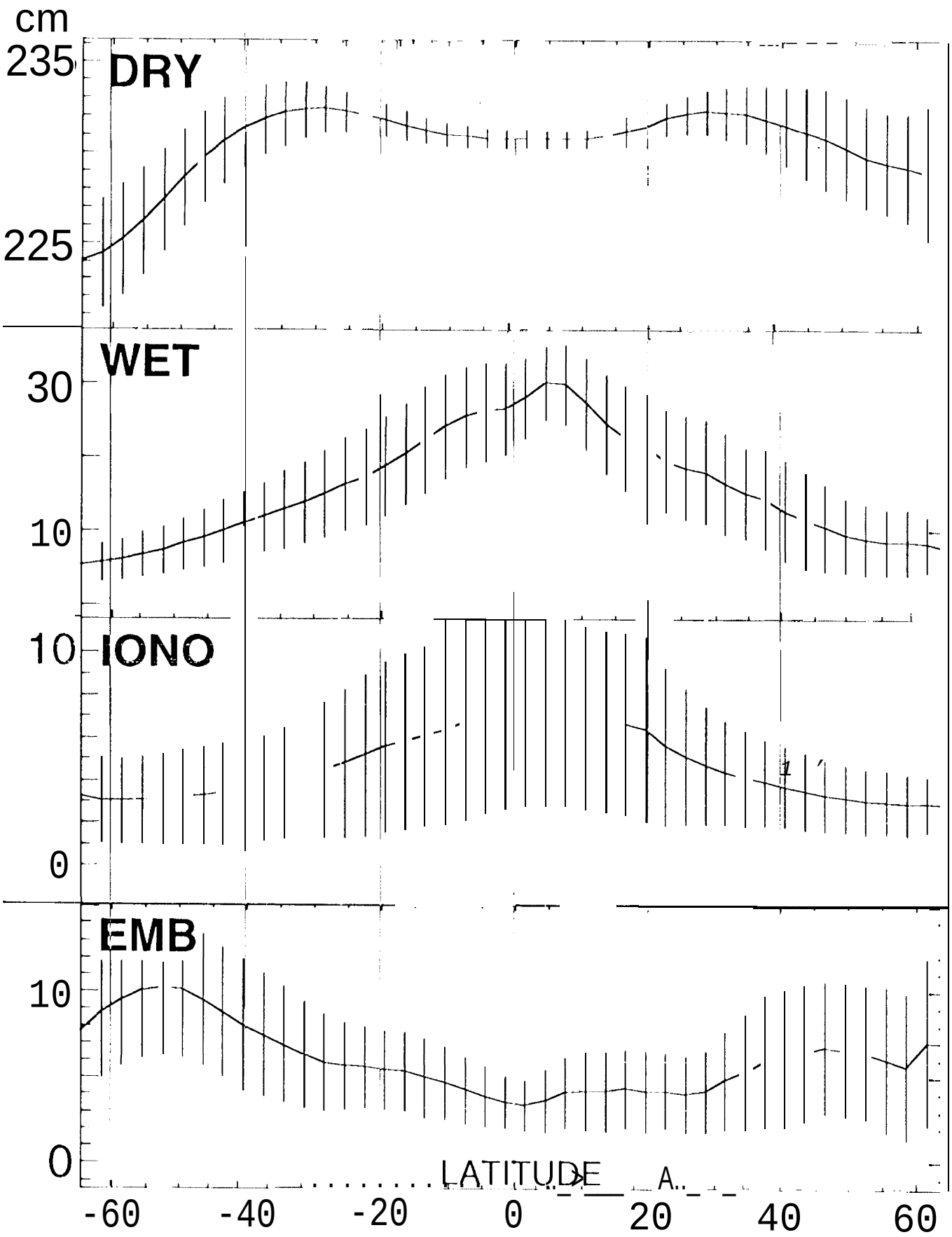
equatorial: within latitudes +/- 20°. (All other rows refer to global values).

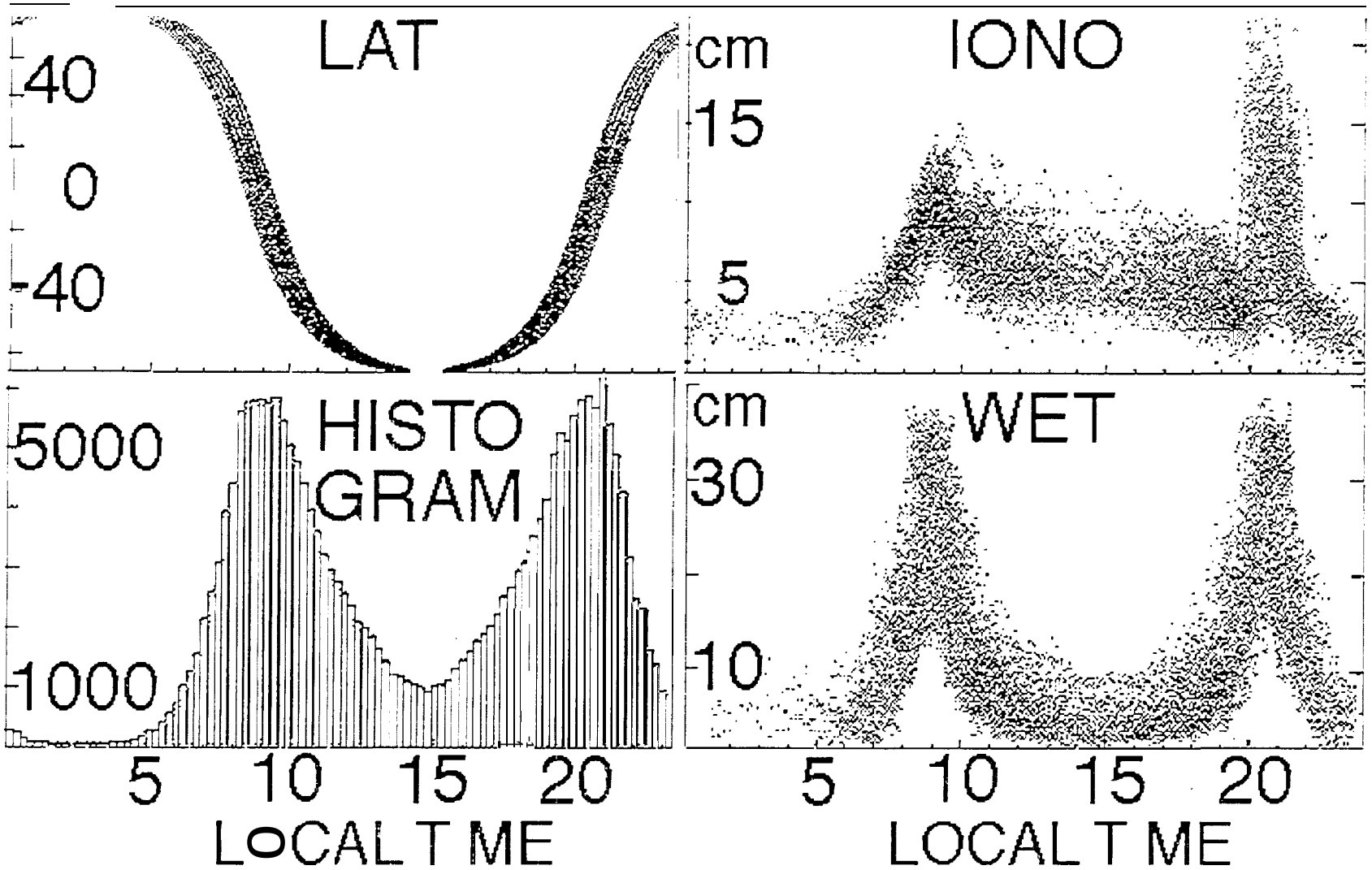
smooth: approx. 90 km a longtrack average.

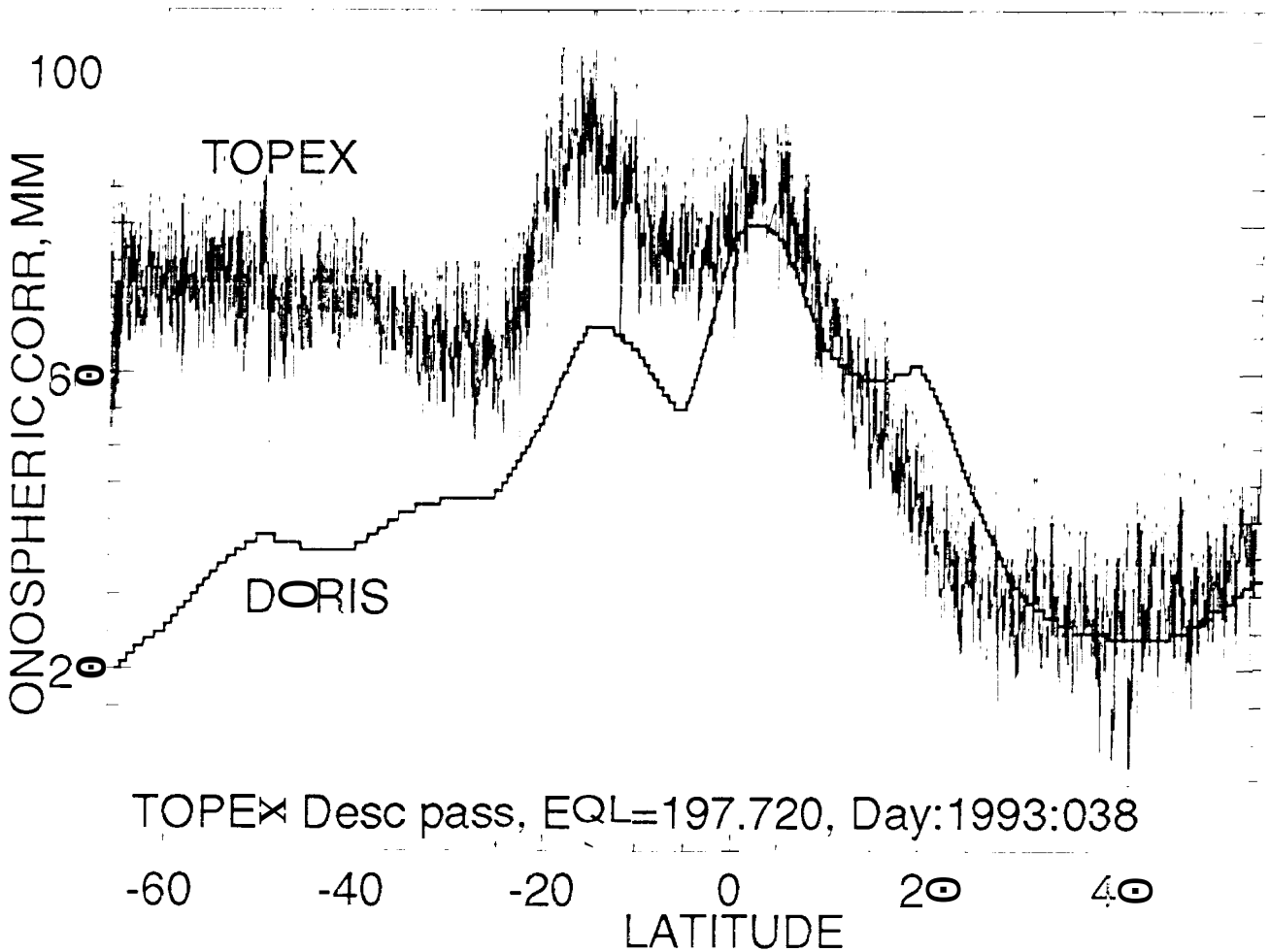
Leftmost 3 columns: from collinear differences (equation .?).

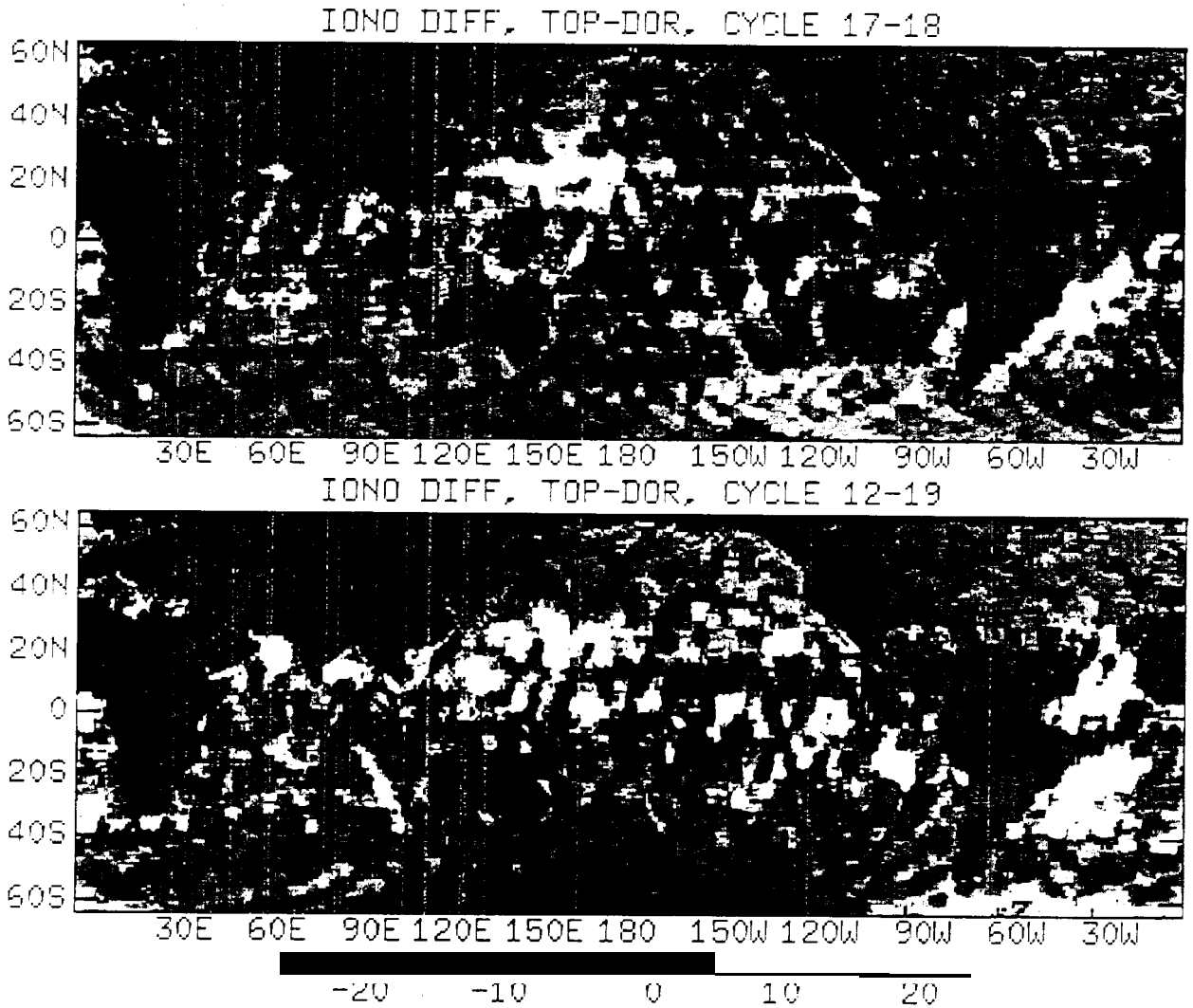
Rightmost 3 columns: full corrections, sea level above OSU MSS.

'INVBAR NOT APPLIED': no inverted barometer correction used in following three rows.


cm
235
225
DRY
WET
30
10
IONO
10
0
EMB
10
0
LATITUDE
-60
-40
-20
0
20
40
60


LAT
40
0
-40
IONO
cm
15
5
HISTO
GRAM
5000
1000
WET
cm
30
10
5
10
15
20
LOCAL TIME
5
10
15
20
LOCAL TIME


100
TOPEX
ONOSPHERIC CORR, MM
60
DORIS
20
TOPEX Desc pass, EQL=197.720, Day:1993:038
-60
-40
-20
0
20
40
LATITUDE


IONO DIFF, TOP-DOR, CYCLE 17-18
60N
40N
20N
0
20S
40S
60S
30E 60E 90E 120E 150E 180 150W 120W 90W 60W 30W
IONO DIFF, TOP-DOR, CYCLE 12-19
60N
40N
20N
0
20S
40S
60S
30E 60E 90E 120E 150E 180 150W 120W 90W 60W 30W
-20 -10 0 10 20