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Seasonal Cosmic-Ray Effects at Sea Level

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By sending a Neher self-recording electroscope in a 10-cm lead shield repeatedly on a slow Norwegian steamer over the route Vancouver–Los Angeles, around South America and return to Los Angeles and Vancouver, we find (1) as heretofore an equatorial dip measured from Los Angeles of seven percent on the western side of South America, eight percent on the eastern side; (2) no measurable seasonal effect, or winter-summer differences, at all in the voyage from Los Angeles to the Straits of Magellan; (3) as heretofore constancy in cosmic-ray intensity in summer and fall, within the limits of uncertainty imposed by fluctuations estimated at not over one percent, on the voyage between Los Angeles and Vancouver; (4) but in winter and spring an increase of as much as two or three percent between Los Angeles and Vancouver. This is interpreted as the atmospheric-temperature effect earlier studied by Hess, Compton, and their respective collaborators.

ALTHOUGH prior to 1934 many of us had reported slight changes in cosmic-ray intensities as a function of temperature,[1] most of these were *positive* in sign and were, at least in part, due, as Bowen and Millikan[2] had found early in 1931, to lack of saturation in pressure electroscopes. However, in 1933 Hess[3] and his collaborators, with the entire elimination of this sort of cause, reported a small but apparently consistent *negative* variation of cosmic-ray intensities "with the temperature of the outer air," that is, for example, a greater intensity by as much as 1.2 percent in winter than in summer, though both the temperature of the electroscope and the barometer remained unchanged. These observers worked on the Hafelekar in Austria, altitude 2300 m, mag. lat. 48.4 N. They used a Steinke cosmic-ray meter shielded with 10 cm of lead. Basing their results on seasonal, rather than daily changes, they reported the coefficient of change $\alpha = -0.047$ percent deg.$^{-1}$ C, and later -0.091 percent deg.$^{-1}$ C.

Also, in 1936 Barnóthy and Forró[4] at Budapest got similarly, with the aid of counters rather than electroscopes, negative coefficient $\alpha = -0.38 \pm 0.05$ percent deg.$^{-1}$ C.

These results, though agreeing in sign, were widely divergent in magnitude, and furthermore we at Pasadena had never found any variation at all of this kind, though we had made careful diurnal, as well as monthly, studies on the constancy of the cosmic rays, and though the

[1] See R. A. Millikan, Phys. Rev. **36**, 1595 (1930) and **39**, 397 (1932); G. Hoffmann, Zeits. f. Physik **69**, 259 (1931); W. Messerschmidt, Zeits. f. Physik **78**, 668 (1932); J. Clay, Proc. Roy. Akad. Amsterdam **23**, 711 (1930).

[2] R. A. Millikan and I. S. Bowen, Nature **128**, 582 (1931); also R. A. Millikan, Phys. Rev. **39**, 397 (1932). Compton, Bennett and Stearns (see Phys. Rev. **39**, 873 (1932)) independently reached the same conclusion.

[3] Hess, Graziader and Steinmauer, Berliner Ber. **22**, 521, 672 (1933); also Wiener Ber. IIa, **143**, 313 (1934); **144**, 53 (1935).

[4] J. Barnóthy and M. Forró, Zeits. f. Physik **100**, 732 (1936).

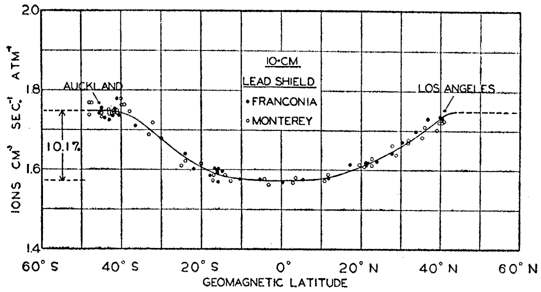

FIG. 1. The two trips here, made seven months apart (mid-summer and mid-winter), show the consistency found on going over the same route at different seasons.

large differences existing in Southern California between the day and night temperatures might well have brought to light a diurnal effect of this type if it existed.

More recently Compton and Turner[5] in sending a recording electroscope repeatedly on a ship plying between Vancouver and Sydney have reported that the increase in sea-level intensities in going from the equator to either Vancouver or Sydney is two or three percent greater in winter than in summer. They have interpreted these differences in terms of the aforesaid "atmospheric-temperature" effect.

The purpose of the present paper is to report upon the bearing upon this effect of the world-wide studies with shielded electroscopes (10 cm lead) of Millikan and Neher on sea-level cosmic-ray intensities.

The earliest pertinent data[6] taken after the development of precision high pressure electroscopes was obtained in July, August and September in Pasadena and in Churchill, Manitoba, when Millikan reported that as a result of week-long studies at both points with the same sensitive pressure electroscope kept at essentially the same mean temperature in both localities he found no change at all between these two points that could amount to as much as one percent. The precision of the reading was much greater than this, but the observed fluctuations were so large as to make it seem unsafe to claim any greater certainty than this.

To check these results as carefully as possible, in September 1932 Millikan and Neher took continuous readings on two different instruments during a five-day ocean voyage between Vancouver and Los Angeles, with the results shown in Table I. We summarized these results in the statement that within the limits of uncertainty of our readings there was no difference in cosmic-ray intensities of more than a percent between the latitudes of Vancouver and Los Angeles.

Again, in December of 1932 and January of 1933 we obtained a mean change of seven percent in sending an electroscope shielded with 10 cm of lead twice between Los Angeles and Mollendo, and in the following winter a 7.1 percent equatorial dip in sending a self-recording instrument on the *Valero III* from Los Angeles to the Galapagos Islands and return. These two trips were made in about the same season and

[5] A. H. Compton and R. N. Turner, Phys. Rev. **52**, 799 (1937); also see A. H. Compton, J. Frank. Inst. **227**, 607 (1939).

[6] R. A. Millikan, Phys. Rev. **36**, 1595 (1930).

TABLE I. *Five-day study of sea-level variations of cosmic-ray intensities between Victoria, B.C. and Los Angeles.**

	Electroscope No. 1—Unshielded (ions cc per sec.)			Electroscope No. 2—Shielded (11 cm Pb)			
	Lat.	4-hour means	12-hour means	Lat.	Long	Mag. Lat.	12-hour means
In Seattle Harbor	47.5	39.58	39.58*	47.5	122 W.	53.5 N.	24.60
In and near Victoria	48.4	39.45	39.45	48.3	123 W.	54.3 N.	24.71
At Sea	47.22	39.53	39.53	46.5	124 W.	52.5 N.	24.65
At Sea	44.4	39.67	39.67	44.0	124 W.	50.0 N.	24.78
At Sea	41.6	39.69	39.69	41.0	124 W.	47.0 N.	24.49
At Sea	39.0	39.34	39.33	37.5	122 W.	43.5 N.	24.79†
In San Francisco Harbor	—	39.82	39.82	36.0	122 W.	42.0 N.	24.57
In San Francisco Harbor	—	39.61	39.61	34.0	119 W.	40.6 N.	24.45†
At Sea	36.85	39.65	39.65			Mean	24.63
At Sea	34.8	39.63	39.65				
		Mean 39.60					

* 8-hour average. † 9-hour average.

are reported for comparison with our new observations, though in themselves they have no bearing on a seasonal effect.

Again, however, in the summer of 1933 and in the winter of 1934, just six months later when a seasonal difference might have appeared, we sent recording instruments on the *Monterey* of the Matson line and the *Franconia* of the Cunard line between Los Angeles and Sydney without bringing to light any seasonal difference at all, as can be seen from Fig. 1, again reproduced here. Indeed, up to the year 1938, neither in our own observing at Pasadena nor in our dozen voyages, had we obtained any definite evidence of seasonal effects, though it is true that most of the voyaging had been done south of magnetic latitude 41°. Further, when our instruments had gone north of magnetic latitude 45° it had been in *summer*.

In March, 1938, however, in order to settle some uncertainties that had been raised as to the precision of our measurements off the coast of South America, and to test for seasonal effects between Los Angeles and Vancouver, we placed still another shielded self-recording instrument on the Norwegian ship *Hoyanger* under Captain Fladmark, which voyages slowly—speed under 10 knots—from Vancouver south to Los Angeles, then all around South America and back to Vancouver, stopping frequently for periods of some days, or even a week, in different ports. The slow speed and the frequent stops of this ship make it particularly well adapted to getting a series of good mean values in the different latitudes traversed.

As appears from Figs. 2 and 3, the results of two voyages made five months apart show no seasonal effect either at Los Angeles or anywhere between there and the Straits of Magellan, though at certain points (e.g. at 20°) the two curves show differences as high as 0.6 percent. This is no larger, however, than the fluctuations in the 4–8-day means taken in port in the same season, indeed, on successive weeks. (See right side of Figs. 2 and 3.) Also, the readings made in late September between Los Angeles and Vancouver check nicely our 1930 and 1932 findings in that they show no changes in intensities between these points. Also, Fig. 2 shows that in these voyages, as in all our preceding ones, there is a seven-percent equatorial dip in going south to the equator from the plateau off the California coast. Also, in this voyage the edge of the plateau is again located, at least in this part of the world, fairly sharply at 41° mag. lat. Also, the dissymmetry brought to light in our preceding voyages between the northern and southern hemispheres is again marked in this one. Finally, as in our preceding reports, so here again we find, though the data shown in the figures do

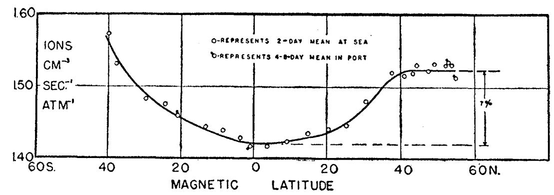

FIG. 2. Cosmic-ray measurements on steamer *Hoyanger*, Vancouver to Cape Horn, September 23rd to November 18, 1938.

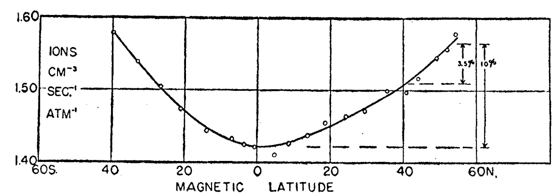

FIG. 3. Cosmic-ray measurements on steamer *Hoyanger*, Vancouver to Cape Horn, May 1st to June 19, 1938.

not cover this point, that the equatorial dip off the east coast of South America rises to eight percent instead of the seven percent found on the west coast.

In marked opposition to these findings, Fig. 3, however, shows a 3.5 percent change between Los Angeles and Vancouver. The fact that the Los Angeles reading remains nearly fixed and the Vancouver reading alone shows the seasonal change proves, if any further proof is needed, that *the change is not due to a magnetic cause.* A change dependent on temperature of the portion of the atmosphere through which the rays come seems the only possible interpretation to put upon these effects, as our predecessors have already concluded.

In Fig. 4 are given the results of three distinct voyages from Los Angeles to Vancouver and return. The voyage made in February and March shows only a two-percent rise between Los Angeles and Vancouver, while that made in

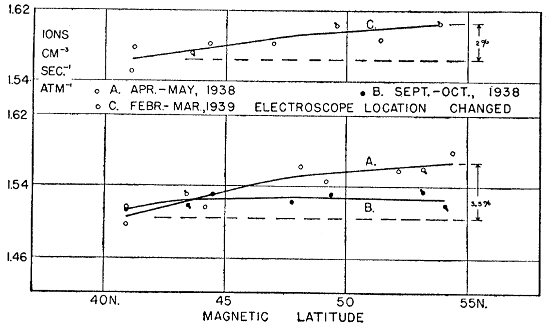

FIG. 4. Cosmic-ray measurements of three distinct voyages from Los Angeles to Vancouver and return.

May shows 3.5-percent change. That the larger change in the Vancouver intensity is found as late as May, instead of in February and March, is a little surprising and may mean that magnetic storms were then adding their effects to the seasonal change, though such a lag in a temperature effect after the astronomical mid-winter season is after all rather in keeping with other climatic lags in this area.

The conclusions that we draw from all of our own readings thus far are, then, (1) that there is no seasonal sea-level effect brought to light by our own readings at Los Angeles, or any point south of there down to the Straits of Magellan, that is of a sufficient magnitude to stand out above the fluctuations observable at the different localities traversed in these voyages; and (2) that between Los Angeles and Vancouver, however, there is a very definite increase in sea-level cosmic-ray intensity of at least two percent in winter that does not appear in summer.

These results are in essential agreement, so far as they go, with the results reported and discussed both by Compton and by Forbush.[7] The latter, by analyzing the data obtained by the Carnegie Institution's cosmic-ray meters running continuously at its stations at Cheltenham (near Washington, mag. lat. 50.1° N.), Teoloyucan (near Mexico City, mag. lat. 29.7° N.), Christchurch (New Zealand, mag. lat. 48.0° S.), and Huancayo (Peru, mag. lat. 0.6° S.), finds no seasonal effect (in his words, "no twelve-month wave") at Huancayo, which is in the equatorial belt. He finds a "twelve-month wave" at Cheltenham amounting to 1.6 percent of the normal cosmic-ray intensity and having the maximum in mid-January. He also finds such a wave at Christchurch (mag. lat. 48.0° S.) having an amplitude of 0.8 percent of the total intensity, its maximum occurring near the end of July (corresponding to the end of January in the Northern Hemisphere). He comments, also, on such a wave at Hafelekar (mag. lat. 48.0° S.) of amplitude 1.9 percent. This may be compared with the smaller of the winter-summer differences found at Seattle. Only in the case of this twelve-month wave of amplitude 1.0 percent at Teoloyucan are Forbush's results apparently somewhat out of line with ours in that, so far as these measurements go, we bring to light no seasonal change at Los Angeles (mag. lat. 41 N.) and none at Cape Horn (mag. lat. 42° S.), both of which are farther from the magnetic equator than is Teoloyucan. The high altitude of Teoloyucan may be the cause of this difference. In a succeeding paper we report upon an attempt to detect the effect of altitude on the seasonal changes.

[7] S. E. Forbush, Phys. Rev. **54**, 975 (1938).