Large-Scale Atmospheric Response to the 1964–65 Pacific Equatorial Warming[1]

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ABSTRACT

Time series of surface winds and sea surface temperatures at Canton Island, covering the period 1962–67, are interpreted to show that the major changes in the temperature of the large central and eastern equatorial Pacific area are caused by the varying strength of the easterly winds and inherent variation in upwelling.

The feedback effects of the ocean temperature variations upon the atmosphere are illustrated by a comparison of the average November 1964 sounding with that of November 1965. In the cold ocean case (1964) the atmosphere has a pronounced stable layer between 900 and 800 mb, preventing convection and rainfall, and in the warm ocean case (1965) the heat supply from the ocean eliminates the atmospheric stability and activates heavy rainfall. The resulting vertical thermal expansion of the tropical troposphere from 1964 to 1965 is demonstrated by 200-mb topographic maps showing the emergence of two new anticyclonic centers symmetrically straddling the equator at the longitude of the maximum ocean warming. The same tropospheric heating can be seen to have been carried far eastward by the upper tropospheric winds, although with diminishing amplitude.

A side effect of the widespread warming of the tropical belt of the atmosphere shows up in the increase of exchange of angular momentum with the neighboring subtropical belt, whereby the subtropical westerly jet strengthens in 1965 compared to 1964 all the way from the central Pacific to the eastern Mediterranean.

The implications of the described ocean-atmosphere interaction for interannual climatic change, and the possible forecasting thereof, are mentioned. It is stressed that climatic forecasting will call for extensive additional coordinated research by oceanographers and meteorologists.

1. The control of the equatorial ocean temperature by the easterly winds

The equatorial belt from the South American coast, 80W, to the dateline is by far the most extensive tropical ocean area showing great interannual temperature variability at the surface. The impact of that oceanic variability upon the global circulation of the atmosphere has recently been demonstrated (see all listed references).

Fig. 1 illustrates the nature of the equatorial ocean-atmosphere interaction observed at Canton Island, 2°46′S, 171°43′W, during 1962–67. The major peaks of sea temperature T_w in late 1963 and late 1965, and the intervening trough in late 1964, were observed in almost identical shape at Christmas Island, 1°59′N, 157°22′W. Puerto Chicama, 7°47′S, 79°28′W, sea temperatures also follow the same major heating and cooling trends, so that it is reasonable to assume that the succession of major temperature changes in Fig. 1 apply to the large body of equatorial water from 80W to the dateline, as also shown recently by Allison *et al.* (1971).

In trying to explain these macro-processes of heating and cooling, the possible radiation anomalies can be ruled out, because over the equatorial ocean cloudiness and rainfall are associated with water heat maxima, and a sunny climate prevails during the periods of cold water. Neither can the heat loss to the atmosphere explain the large oscillations of sea temperature, because the atmosphere in contact with the ocean is cooler than the water during periods of warm ocean and warmer than the water during periods of cold ocean.

It remains to invoke the variability of water advection from the east, and from below, as the explanation of the observed macroscale temperature changes in Fig. 1. The periods of subnormal ocean temperature T_w are by and large also the periods of strong easterly winds u, which must have strengthened both the drift current from the east and the upwelling. The variation in upwelling seems to be the most important contributor to the variations in equatorial sea temperatures, but a quantitative assessment of the relation between the cooling produced by upwelling and by advection from the east is still lacking. Lateral water mixing by eddies is of course also to be taken into account in explaining the broadening of the cold water tongue on either side of the active equatorial upwelling.

In addition to the parallelism of the curves for ocean temperature and easterly wind, Fig. 1 also shows shorter period "noise" of u unrelated to any corresponding features in the T_w curve. These short-period

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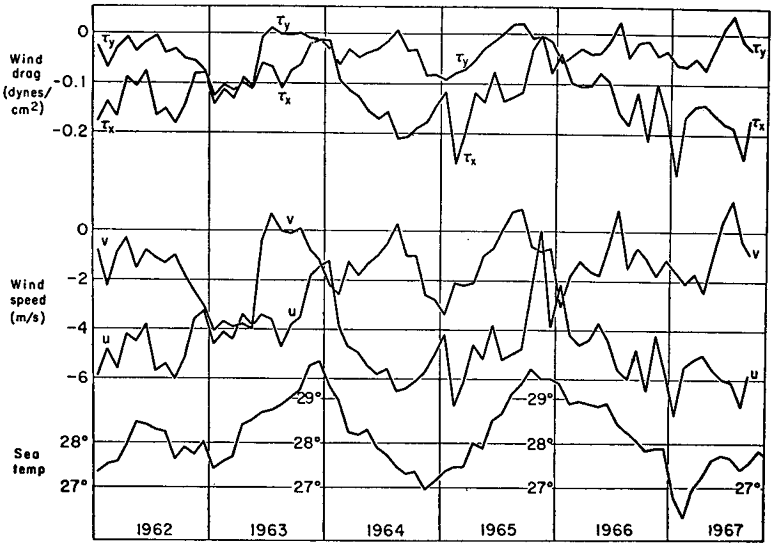

FIG. 1. Time series of Canton Island sea temperature T_w, zonal u and meridional v components of surface wind, and wind drag components, τ_x and τ_y.

variations of u must be of atmospheric origin and all impulses of that kind apparently fail to produce visible response in T_w.

2. The feedback from the ocean

Fig. 2 shows a comparison of Canton Island monthly averaged temperature soundings for November 1964, at the phase of cold ocean, and for November 1965 at the following phase of warmer ocean. The cold ocean case maintains a well-marked stable layer from 900 to 800 mb which puts an efficient lid over any convection that may develop in the layer next to the ocean surface. The warm ocean case has no such inversion and cumulus clouds can then grow into cumulonimbus in an atmosphere of close to moist adiabatic lapse rate. In the layer 850–500 mb the sounding above the warm ocean is not any warmer than that over the cold ocean, but the "hot cumulonimbus towers" above 500 mb and the sinking motion between them makes the convective atmosphere warmer than the dry non-convective atmosphere over the cold ocean. The total column from sea level to 200 mb does expand vertically by a moderate amount from the cold ocean to the warm ocean phase (see Figs. 3 and 4).

The soundings at Hilo at 20N, also in Fig. 2, reveal a much greater tropospheric warming, and greater lifting of the 200-mb surface, from November 1964 to November 1965, than what was observed at the equator. Meanwhile, the soundings at weather ship N at 30N shows the opposite change in tropospheric temperature, namely a considerable cooling and inherent descent of the 200-mb surface from November 1964 to November 1965.

A comparison of the maps of 200-mb topography in November 1964 (Fig. 3) and November 1965 (Fig. 4) shows clearly why the upper troposphere over Hilo did warm up so much. In 1964 the air came to Hilo from Asia at about 30N, whereas in 1965 it came from the equatorial belt moving around the western end of an anticyclone, hereafter referred to as a Hadley anticyclone, which was non-existent the year before. A corresponding re-arrangement of the 200-mb air trajectories leading to Fiji, south of the equator, produced equally big upper tropospheric warming as in Hilo. And

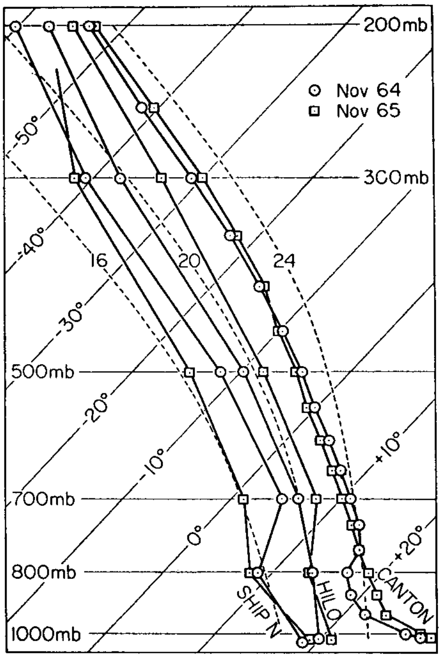

FIG. 2. Monthly averaged soundings for November 1964 and November 1965 for Canton Island (2°46′S), Hilo (19°43′N) and Ship N (30N). Dashed lines are moist adiabatics.

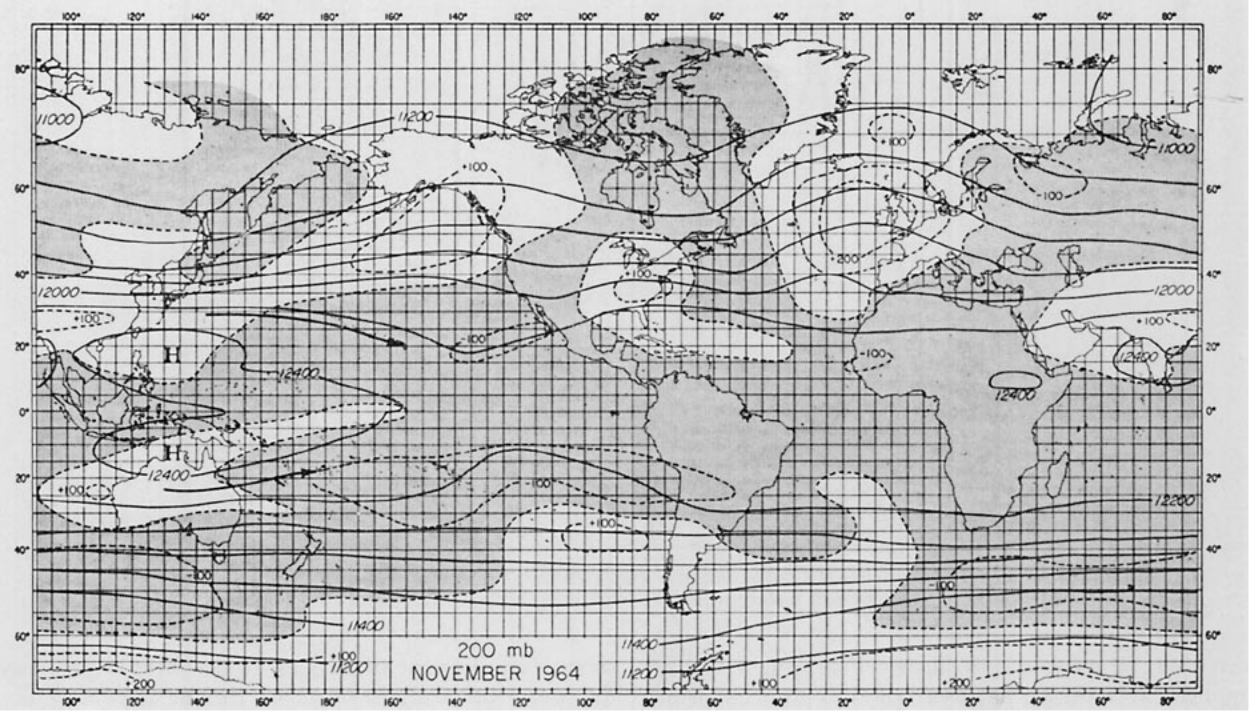

FIG. 3. 200-mb gpm topography for November 1964 and gpm change from November 1963. Negative change areas are shaded.

the cause of such warming can in both cases be traced back to the considerable warming of the equatorial ocean and the escape of equatorial air toward subtropical latitudes around the western end of the new twin Hadley anticyclones.

In Figs. 3 and 4 shading indicates decreases of 200-mb

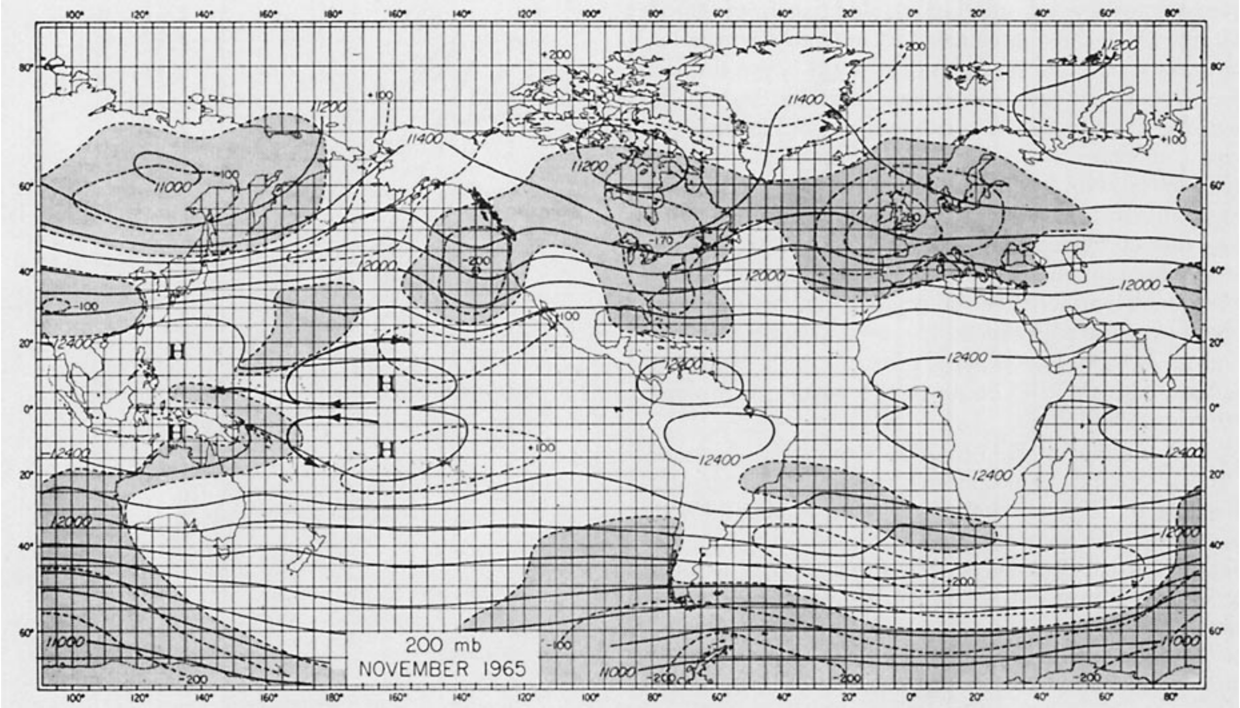

FIG. 4. 200-mb gpm topography for November 1965 and gpm change from November 1964. Negative change areas are shaded.

height from the month of November in the preceding year. The non-shaded area in Fig. 4 obviously embraces the two central Pacific Hadley anticyclones, north and south of the equator. But, somewhat unexpectedly, the increase of 200-mb heights has also spread eastward along the tropical belt almost around the globe. This applies then also to the strengthening of the 200-mb westerlies from November 1964 to November 1965, which is particularly well shown by the change at about 30N from increasing tropical 200-mb heights to decreasing extratropical 200-mb heights extending from the mid-Pacific eastward across North America and the Atlantic to the eastern Mediterranean.

The two global circulations (Figs. 3 and 4), being separated in time by a full annual cycle of seasonal change, differ most likely because of the intervening progressive 12-month equatorial warming over the earth quadrant from the dateline to South America, but perhaps also because of other kinds of influence. It is therefore of great interest to see a dynamical simulation of the effect on the atmospheric circulation of a sudden warming of the east Pacific equatorial quadrant separated from all other conceivable disturbances.

This task has recently been performed with Smagorinski's 9-level atmospheric model at NOAA's Geophysical Fluid Dynamics Laboratory, by the visiting British meteorologist Rowntree. His four 30-day integrations, two with warm and two with cool tropical east Pacific, show that the upper Hadley anticyclogenesis located over the tropical quadrant of surplus ocean warming, is fully developed after 20 days of simulated development. And, also, during the same spell of time the upper tropospheric lifting of pressure surfaces has spread far eastward along the tropical belt with decreasing but yet significant amplitude, whereas no westward spreading resulted. This imitates very well the change from Fig. 3 to Fig. 4 and supports the assumption that the fluctuations of the atmospheric tropical circulation must be rather firmly controlled by the instantaneous anomalies of equatorial ocean temperatures.

A forecaster at work on macroscale long-range prediction would have known about the beginning of the 1964–65 equatorial ocean warming by reports from Canton and Christmas Island in early 1965, but the warming did not reach sufficient amplitude to cause upper anticyclogenesis over the northern subtropics during what was left of the northern winter season. During the summer of 1965 the equatorial ocean warming continued, but the summer season with its even stronger extratropical warming remained a time of minimum baroclinity, so that the Hadley circulation had to remain weak over the northern subtropics. In September 1965, with the equatorial ocean temperature well above normal (see Fig. 1), the upper Hadley anticyclone, separate from the Indonesian one, appeared with its center at about 10N, 175W. In October 1965, as predicted in Rowntree's simulation, the tropospheric warming and the rise of the 200-mb heights had spread far eastward across South America and Africa. The forecaster at this stage could also check the equatorial surface pressure changes from 1964 to 1965 and find negative values within the long stretch from the dateline eastward to Africa (see Fig. 6) and positive values west of the dateline (Southern Oscillation). He could then conclude that the stage was set for the Pacific Hadley anticyclone to operate very soon in the pre-winter increasing baroclinity and pump much westerly angular momentum into a 30N jet stream. That feature is seen to extend in Fig. 4 from the mid-Pacific to the eastern Mediterranean.

The resulting early beginning of the rainy season in Southern California as well as in Southern Europe could have been predicted with a cautious probability rating in September and with more certainty in October.

A comparison between the surface pressure maps in Figs. 5 and 6 shows that, whereas in November 1964 the anticyclones at 30N, 140W and 38N, 17W prevented rain in Southern California and Southwestern Europe, November 1965 brought plenty of rain to those two regions from the cyclonic systems centered, respectively, off the coast of British Columbia and over southern Britain. These two surface centers are located under the zone of cyclonic shear vorticity on the northern flank of the newly formed 200-mb jet stream from the mid-Pacific to the eastern Mediterranean.

3. The far northern circulation changes

Whereas the creation of the subtropical westerly jet from the mid-Pacific to the eastern Mediterranean can be understood as a relatively simple dynamical consequence of the 1964–65 equatorial Pacific warming, the simultaneous large-scale changes of the atmospheric circulation farther north call for more complex dynamic explanations. Even so, I think one can see that the low-latitude changes triggered those farther north.

The Iceland low, normally centered at 62N, 30W did lose its supply of warm moist air from the southwest as a consequence of the low pressure development over Britain. The weak remnants of what was the Iceland cyclone is in November 1965 located on the Labrador coast at 55N, 60W.

The Aleutian low has also been displaced westward from 1964 to 1965, giving room for the anticyclogenesis centered north of Hawaii as the low-level part of the 200-mb anticyclogenesis south of Hawaii in Fig. 4. But the Aleutian low did not lose its warm air supply. On the contrary, the transport of warm air from lower latitudes is much more efficient in Fig. 6 than it was in Fig. 5. The intensification of the Aleutian low from 1964 to 1965 is therefore easily explained.

The intensification of the Aleutian low brought about an interannual fall in surface pressure of 20 mb at 70N, 165E, with the negative pressure change extending over one-third of the 70N circumference. The re-

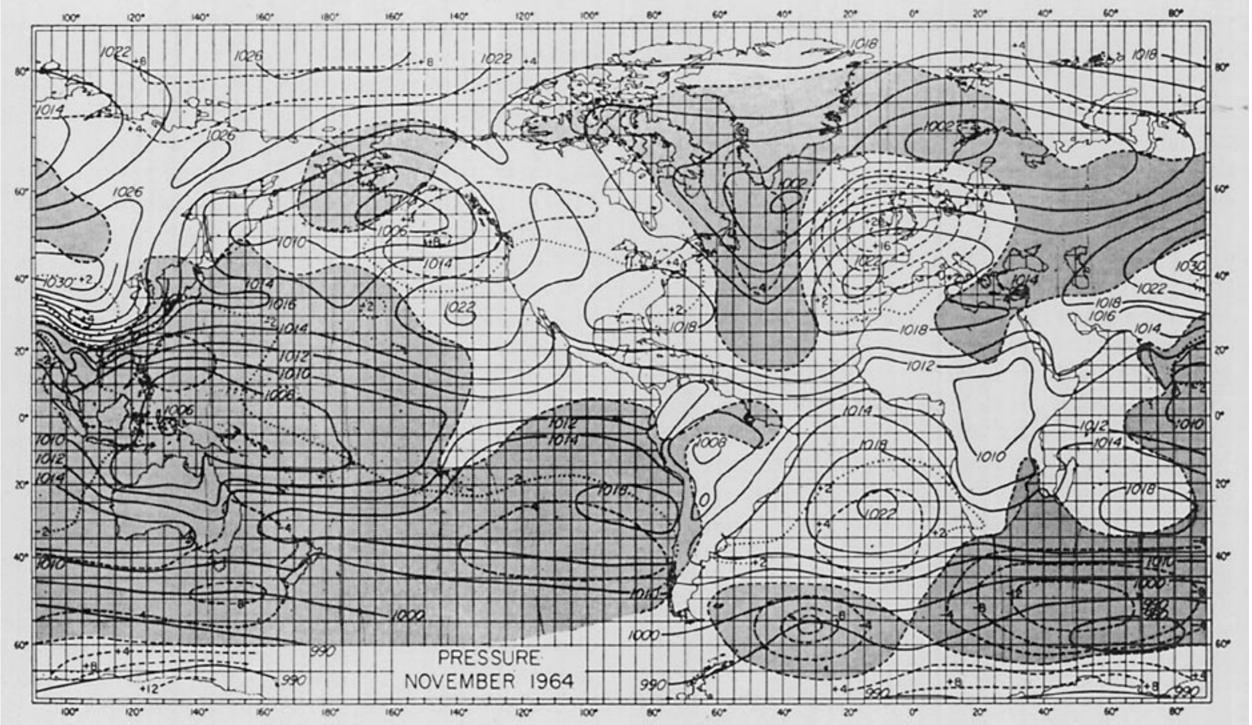

FIG. 5. Surface pressure field for November 1964 and pressure change from November 1963. Negative change areas are shaded.

maining two-thirds had a positive pressure change with a maximum of 15 mb at southeast Greenand. These two large opposite systems of pressure chlange must have had a common cause, presumably presented by the Aleutian storm activity, and a circumpolar transmission of wave energy by a stationary Rossby-type

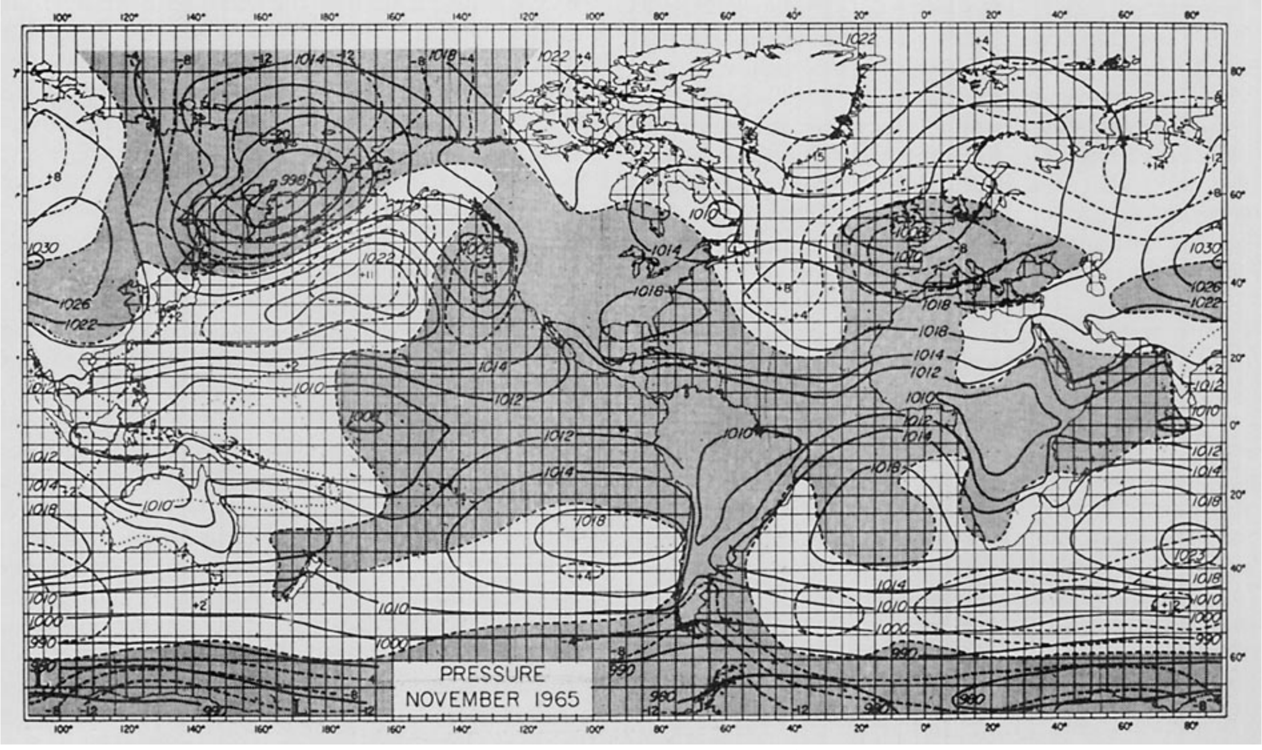

FIG. 6. Surface pressure field for November 1965 and pressure change from November 1964. Negative change areas are shaded.

one-wave pattern of the upper westerlies. The 200-mb map (Fig. 4) shows a 360° standing wave with its trough over east Asia and ridging over Greenland. However, the two-wave pattern is also there, as represented by the east Asian and east Canadian troughs which are tied to the Kuroshio and the Gulf stream heat sources. It is apparently when the Aleutian low is strong, and the Iceland low much weaker, that the one-wave pattern takes over in high latitudes.

The above discussion of the high-latitude teleconnections from a tropical atmosphere above anomalously cold or anomalously warm tropical ocean water is of course incomplete and should be extended by a month-to-month global analysis of the effect of the 1964–65 equatorial warming (as well as other analogous cases).

4. Conclusion

The variability of the heat and moisture supply to the global atmospheric thermal engine from the equatorial Pacific can be shown to have far-reaching large-scale effects. The dynamic mechanism of such teleconnections can at present be intuitively surmised, and has been experimentally simulated by Rowntree (1972) with Smagorinski's 9-level atmospheric model.

An essential further step will be to explore, by new oceanographic techniques, the ocean-atmosphere interaction leading to future large-amplitude rhythms of ocean temperature, as exemplified in Fig. 1. This should finally provide the data base for realistic predictive models in the monthly range.

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