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COO-1542-64

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ON THE INTERANNUAL VARIABILITY OF THE OCEAN ATMOSPHERE SYSTEM*

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ABSTRACT

Several feedback mechanisms between ocean and atmosphere are discussed, which seem to have a decisive influence on the interannual variability of the atmosphere and on climatic fluctuations on a time scale of 10 to 50 years. Satellite requirements to monitor these feedback processes are outlined briefly.

It has been pointed out by several authors [1], [2] that large sea-surface temperature (SST) anomalies in the North Pacific, but also in the North Atlantic can, at times, influence weather patterns downstream by influencing the behavior of planetary long waves. So it has been surmised that the excessively cold winter of 1976-77 over the Eastern United States was to a considerable part due to a large negative SST anomaly in the central North Pacific which reached maximum proportions during summer and fall of 1976.

Our own preliminary research results indicate that SST anomalies can, indeed, amplify certain planetary wave patterns (mainly hemispheric wave numbers 2 and 3) if these anomalies are of the right sign and in the right location to cause

*The research reported in this paper was supported by NASA, Goddard, Grant NGR 06-002-098, U.S. DOE Grant EY-76-S-02-1340, NSF Grant ATM76-21017 and NOAA Grant N00228-76-C-3205.

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"resonance" with the orographically forced planetary wave modes.

In order to understand some of the interannual variability of regional weather patterns caused by the variability of planetary wave modes, we have to come to grips with the effects of SST anomalies on the atmosphere and, ultimately, with the causes for SST anomaly generation. Research into both problem areas presently is severely hampered by insufficient data. To estimate SST anomalies and air-sea interaction by latent and sensible heat transport we rely mainly on observational data from ships of opportunity [3], [4], [5], [6]. These data are sparse and noisy and have to be subjected to smoothing and interpolation routines before they can become useful. Figure 1 gives an example of SST anomalies in the North Pacific obtained from different data sources in the latitude band 40 - 50°N. The incompatibility of the NOAA data set with later data material is most likely caused by neglected systematic temperature variations within each "grid box".

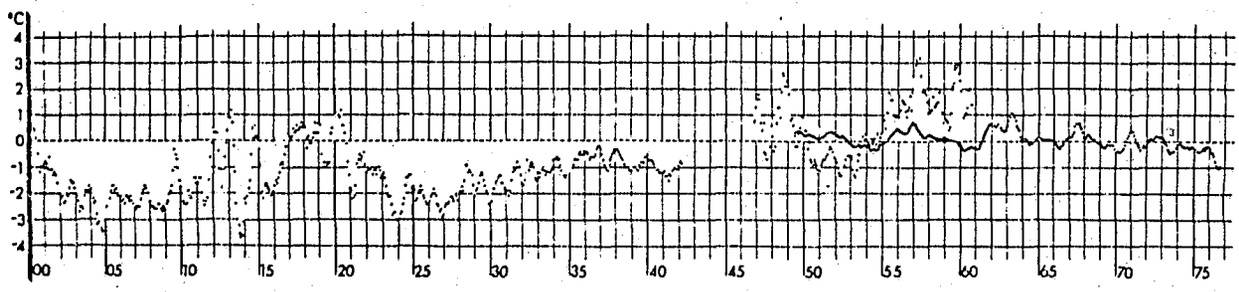

Fig. 1. Seven-month running mean of sea surface temperature anomalies (°C) in the latitude band 40-50°N of the North Pacific, calculated with respect to the 1962-1976 monthly mean temperatures. Dots after 1962, data from Fleet Numerical Weather Central; solid line between 1949 and 1962, data from Fisheries Research Board of Canada; dots prior to 1962, data from National Oceanic and Atmospheric Administration.

With sufficient smoothing and time-averaging even our present data base reveals considerable systematic and interannual variability in SST anomalies. Figures 2

and 3 show the monthly departures from the monthly mean values of SST's averaged by latitude band in the Pacific and Atlantic. Of special interest is a long-term cooling trend in the Pacific between 40 and 50°N, which seemed to have set in around 1963 (compare with Fig. 1). At 50 to 60°N the cooling trend started not until 1967. Long-term trends in the Atlantic, as well as shorter-term SST anomalied superimposed upon these trends, are not identical to those in the Pacific.

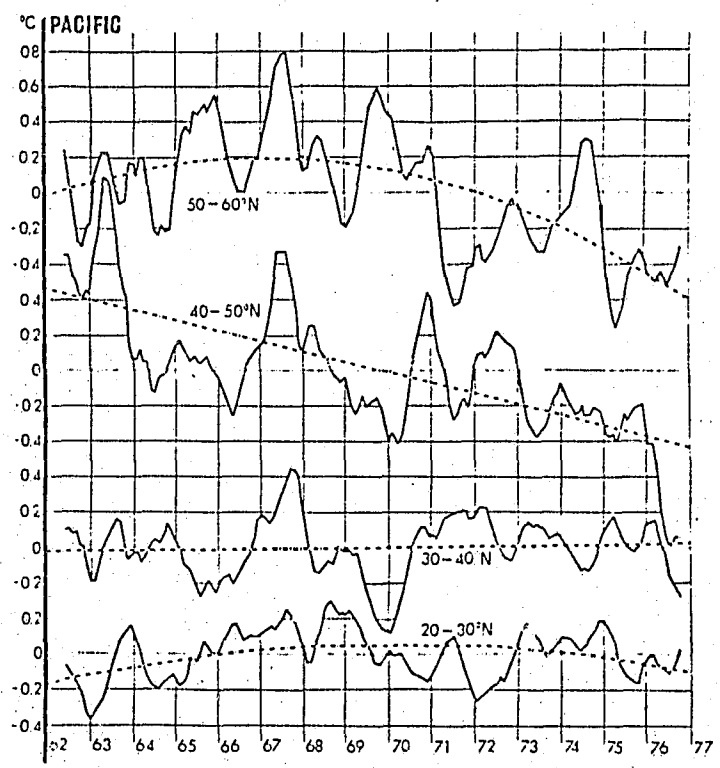

Fig. 2. Monthly SST anomalies in the North Pacific (°C) averaged over the latitude bands as indicated. A seven-month running-mean filter has been applied to the monthly anomaly data. Dashed-dotted lines indicate the least-squares fit of first-, second-, or third-order polynomials.

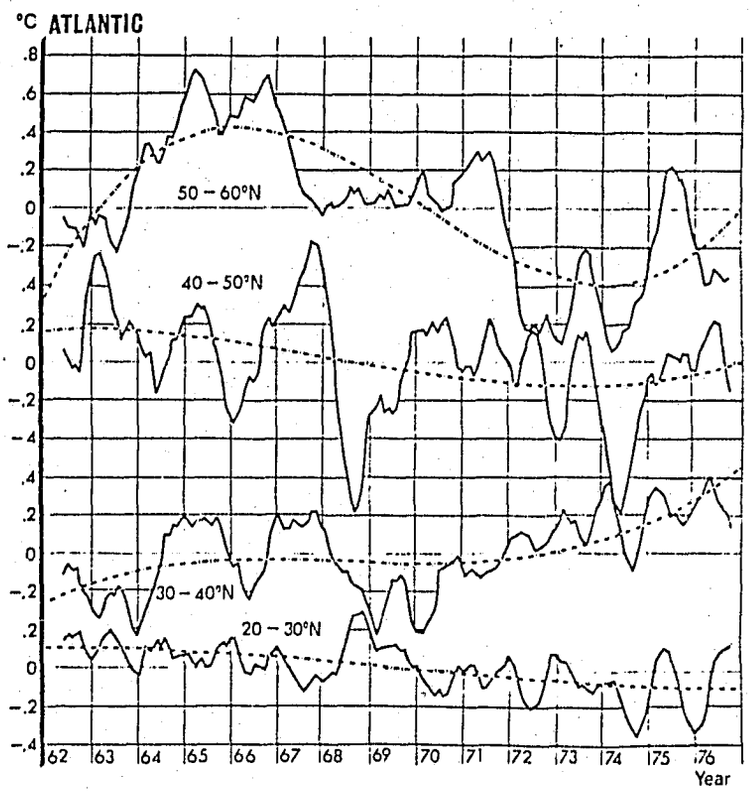

Fig. 3. Similar to Fig. 2, except for Atlantic.

The origin of SST anomalies still remains a puzzle, mainly because the errors and lack of time and space resolution in our present data base do not permit accurate assessment of the various quantities that enter into the heat balance equation of an oceanic "box". As illustrated in Fig. 4, this balance can be written as follows

$$Q_\theta = Q_{IS} + Q_{HA} - Q_{OL} - Q_{SH} - Q_{EV} - Q_{UW} - Q_D \qquad (1)$$

where Q_θ is the heat contained in the oceanic volume that reveals the observed SST anomaly. Presumably this volume will contain a major part of the mixed layer above the thermocline and will not be confined to just a shallow surface layer, if the SST anomaly under consideration is significantly long-lived.

In Figs. 2 and 3 we have removed the seasonal trends, hence we should consider <u>anomalies</u> in the budget terms listed in equ. (1). Q_{IS} then would be an anomaly in

the heat gain by incoming radiation from sun and sky, produced mainly by anomalous cloudiness conditions. We have not yet had the opportunity to assess the significance of this term on SST anomaly generation, but satellite data will have to figure prominently in such an assessment.

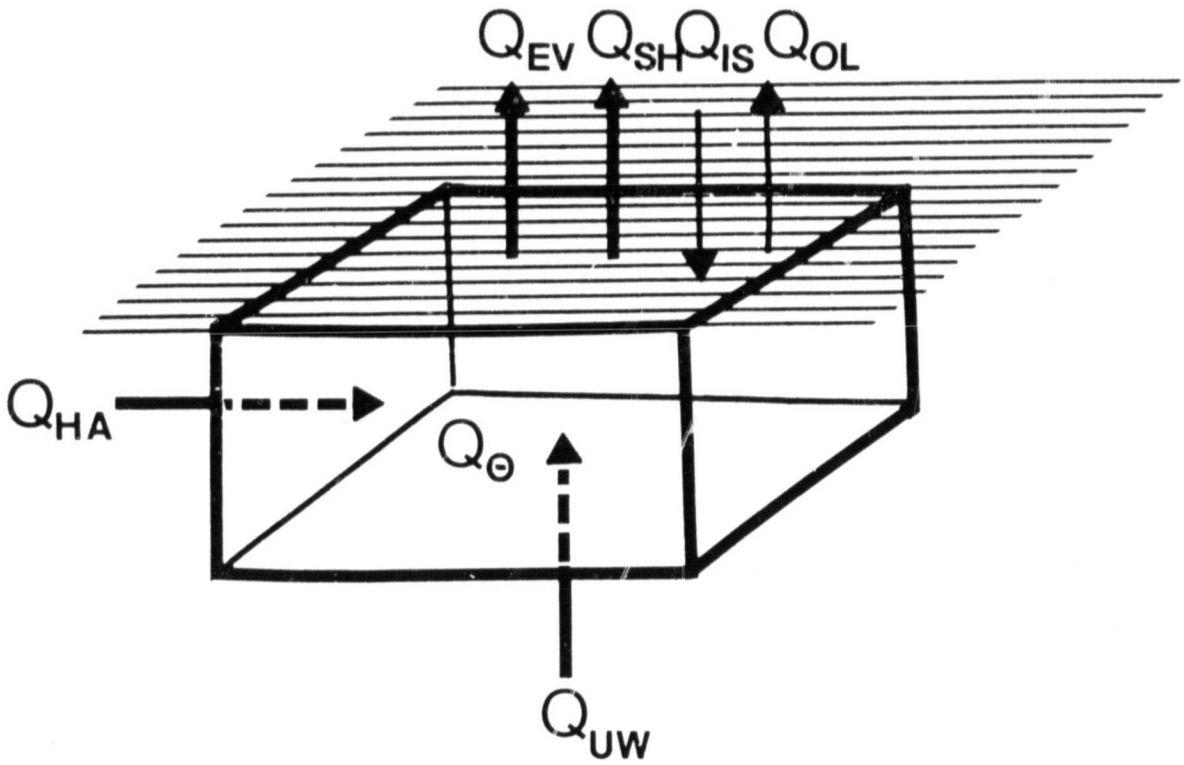

Fig. 4. Schematic diagram of the energy budget of an oceanic volume situated in the mixed layer underneath the (striped) ocean surface.

$-Q_{OL}$ is the heat loss by the ocean, mainly by long-wave radiation. This term depends on the oceanic surface temperature, but also on atmospheric transmissivity modulated by cloudiness and water-vapor anomalies. Again satellite data will have to figure prominently in an evaluation of the significance of this term.

Q_{HA} is the heat gain (or loss) by variations in the horizontal advection through the ocean currents moving in and out of the SST anomaly area under consideration.

Into the term Q_{HA} will enter variations of heat transport along the mean current streamlines, but also effects of the displacement of the current systems in a direction perpendicular to the mean streamlines.

$-Q_{SH}$ covers the heat loss to the atmosphere by sensible heat transfer and $-Q_{EV}$ is the heat loss by evaporation (latent-heat transfer). Heat losses or gains by precipitation of a temperature different than that given by SST have been neglected.

Q_{UW} covers the effects of upwelling through the mean level of the thermocline, produced mainly by Ekman pumping. Recent investigations [7], [8] seem to indicate that Ekman pumping played, at best, a minor role in the development of the large negative SST anomaly in the North Pacific during 1976. Q_D contains the effects of sub-grid scale diffusion.

We are not yet in a position to examine each term of the balance equation (1) in quantitative detail. We have attempted, however, to explore the possible impact of some of the terms on SST anomaly formation.

Seigel [6] computed daily values of latent and sensible heat transport from the ocean to the atmosphere using bulk transfer equations applied to gridded data of SST, air temperatures, vapor pressures and (geostrophically derived) wind speeds at ship-deck level received from the U.S. Fleet Numerical Weather Central.

Figure 5 shows examples of daily mean values of sensible and latent heat transfers from the North Atlantic and Pacific for the period October 1972 - December 1973. Values comprise averages for the oceanic areas north of 20°N. A considerable

amount of interdiurnal variability of mean heat fluxes is evident from these diagrams, whose spectra reveals peaks at periods of approximately 7 days and 22 - 24 days. The former period appears to be tied to traveling cyclonic disturbances, the latter to a vacillation in the atmospheric energy cycle investigated earlier [9]. Table 1 reveals a considerable interannual variability of the sensible heat flux, especially during winter when flux values are high.

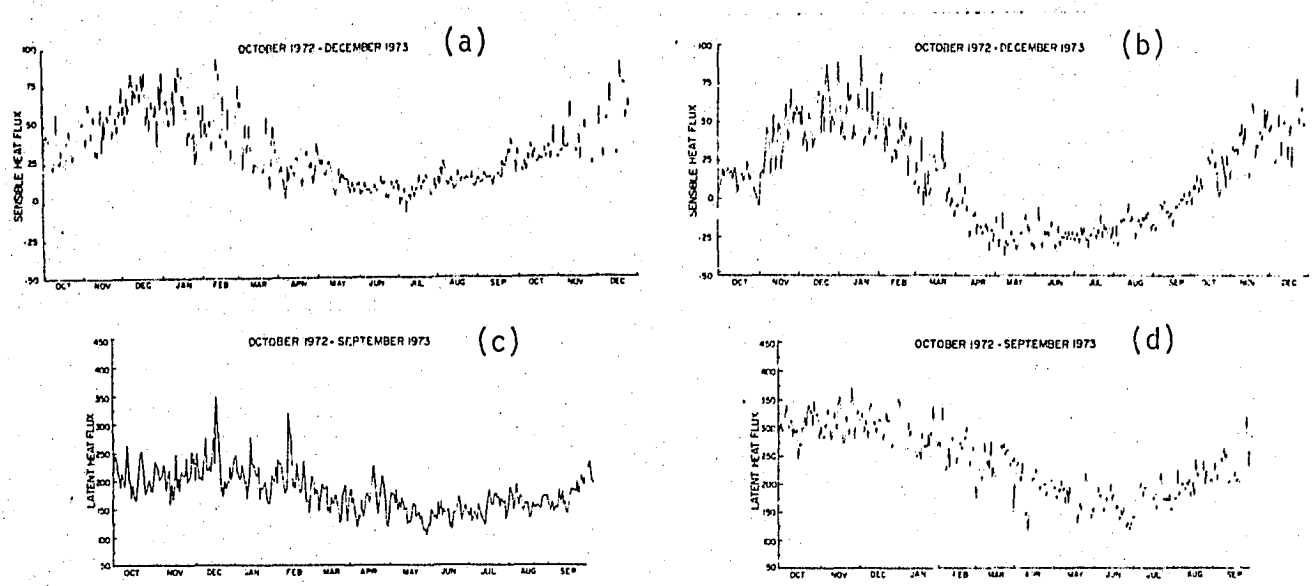

Fig. 5. Daily values of sensible and latent heat transfer (cal cm^{-2} day^{-1}) averaged over the oceanic areas of the Pacific and Atlantic north of 20°N for the period indicated. (a) Sensible heat transfer, Atlantic; (b) sensible heat transfer, Pacific; (c) latent heat transfer, Atlantic; (d) latent heat transfer, Pacific. (After [6].)

The short-term variability in the ocean-to-atmosphere heat transfer is strongly influenced by variations in the wind speed. We suspect that some of the interannual variability in this transfer also depends on the degree of "storminess", especially in middle latitudes. This hypothesis will have to be checked further, however.

TABLE 5* Mean Fluxes of Sensible and Latent Heat From the Ocean to the Atmosphere, for Regions North of 20°N

	Sensible Heat Flux (cal $cm^{-2}day^{-1}$)		Latent Heat Flux (cal $cm^{-2}day^{-1}$)	
Oct. - Mar.	Atlantic	Pacific	Atlantic	Pacific
1970-71	47.55	31.45	207.03	274.27
1971-72	48.10	35.13	194.74	270.55
1972-73	49.05	36.70	201.37	281.74
1973-74	42.56	33.71	195.26	269.51
1974-75	47.17	36.94	192.10	268.26
Average	46.89	34.79	198.10	272.87
Stand. Dev.	2.25	2.04	5.40	4.87
% of S.D.	5%	6%	3%	2%

*Data after Seigel, 1977.

Satellite surveillance of atmospheric water vapor content and of water vapor flux divergence over the ocean should be compared against some of the latent heat transport calculations quoted above, that employed conventional ship data. If the interannual variability of latent heat transport evident from Table 1 can be considered real we should suspect a similar variability to characterize hemispheric precipitation. This variability, however, is below the threshold value of resolution of our present precipitation measurement system.

The generation of SST anomalies by horizontal advective processes is also difficult to assess from our present data base, mainly because of the sparsity of oceanic current and flow information. Figure 6 shows current velocities in two areas identified in Fig. 7. Current velocity data were obtained from the National Oceanographic Data Center (NODC), Washington, D.C. Monthly values were interpolated linearly for missing time periods and then a 7-month running-mean filter was

applied to the data. Area 2 is characteristic of the Kuroshio Extension [10], whereas Area 1 is expected to be subject to some of the Oyashio effects, even though it lies rather close to Area 2.

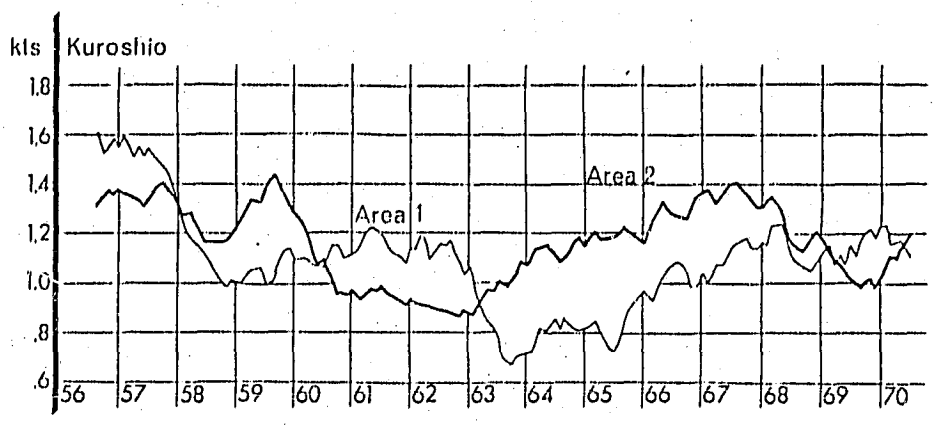

Fig. 6. Current velocities in m/sec, averaged over observations in Area 1 and 2 identified in Fig. 7. Values for missing months were obtained by linear interpolation. A seven-month running-mean smoothing filter was applied to the monthly velocity values.

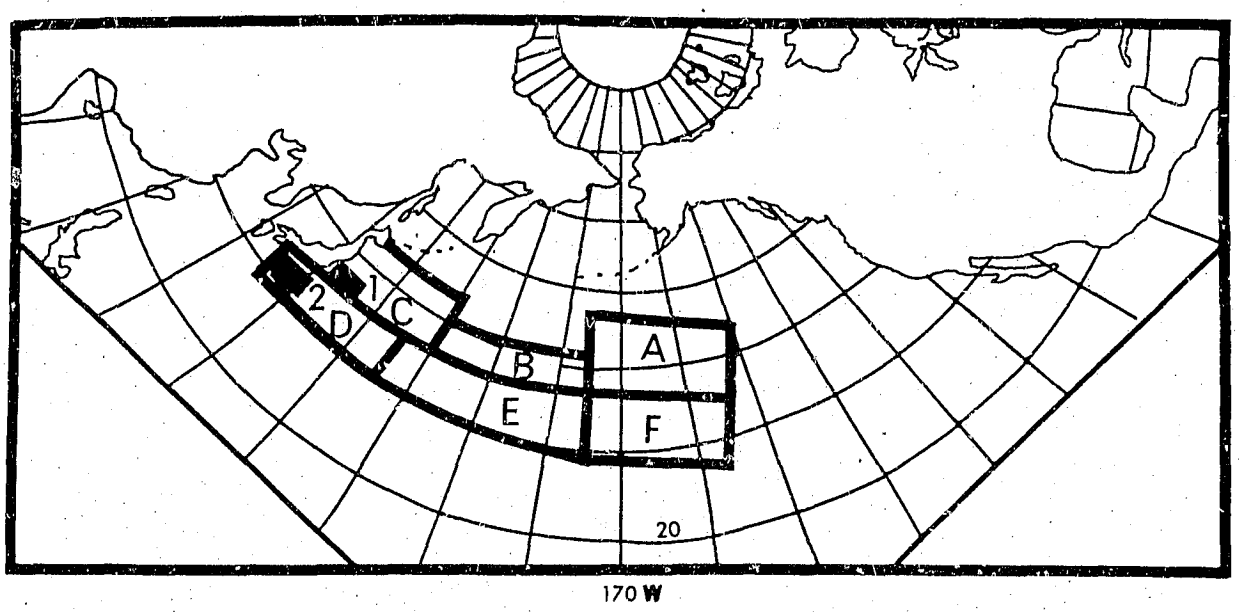

Fig. 7. Location map of oceanic areas used for averaging purposes.

In Fig. 7 we have also indicated the areas A through F used for SST calculations. The northern tier of areas, indeed, shows temperatures approximately 7°C lower than the southern tier, indicating the involvement of two different current systems. The current velocities in Fig. 6 do not directly reveal the water transport variations in Areas 1 and 2. To arrive at the latter we would have to know the velocity distribution and depth, and the width of the currents. Nevertheless, a few qualitative comparisons shall be attempted.

Figure 8 shows the 7-month smoothed SST anomalies averaged over areas A through F defined in Fig. 7. Area A experienced a pronounced cooling trend between 1964 and 1970, interrupted by a warm period in 1967. The long-term trend -- but not its interruption -- agrees with the increase of cold water transport in Area 1 (Fig. 6) during the same time period. Area 2, on the other hand, appeared to contain increasing current velocities between 1962 and 1967 and a decline thereafter. The general trends of SST in area D -- ignoring shorter-term fluctuations for the time being -- indicate warming between 1962 and 1967, and cooling thereafter.

The SST anomalies in Area C, which also contains Area 1, shows strong cooling between 1962 and 1965 and considerable warming thereafter. It appears as if this area as well as the downstream areas B and A between 1966 and 1970 experienced temperature surges similar to area D. Thereafter the similarity between D and C ceases again.

Possible advective properties of SST anomalies are somewhat masked in Fig. 8 by the smoothing filter that has been applied to the data. Nevertheless, some of the positive anomaly peaks indicate a time delay between areas D, E and F of 2 to 3 months between each area. The original, unsmoothed values reveal such a delay

somewhat better. The same is the case for negative anomaly peaks in areas C, B and A. We are presently in the process of quantifying these lag-correlations between SST anomalies of adjacent areas.

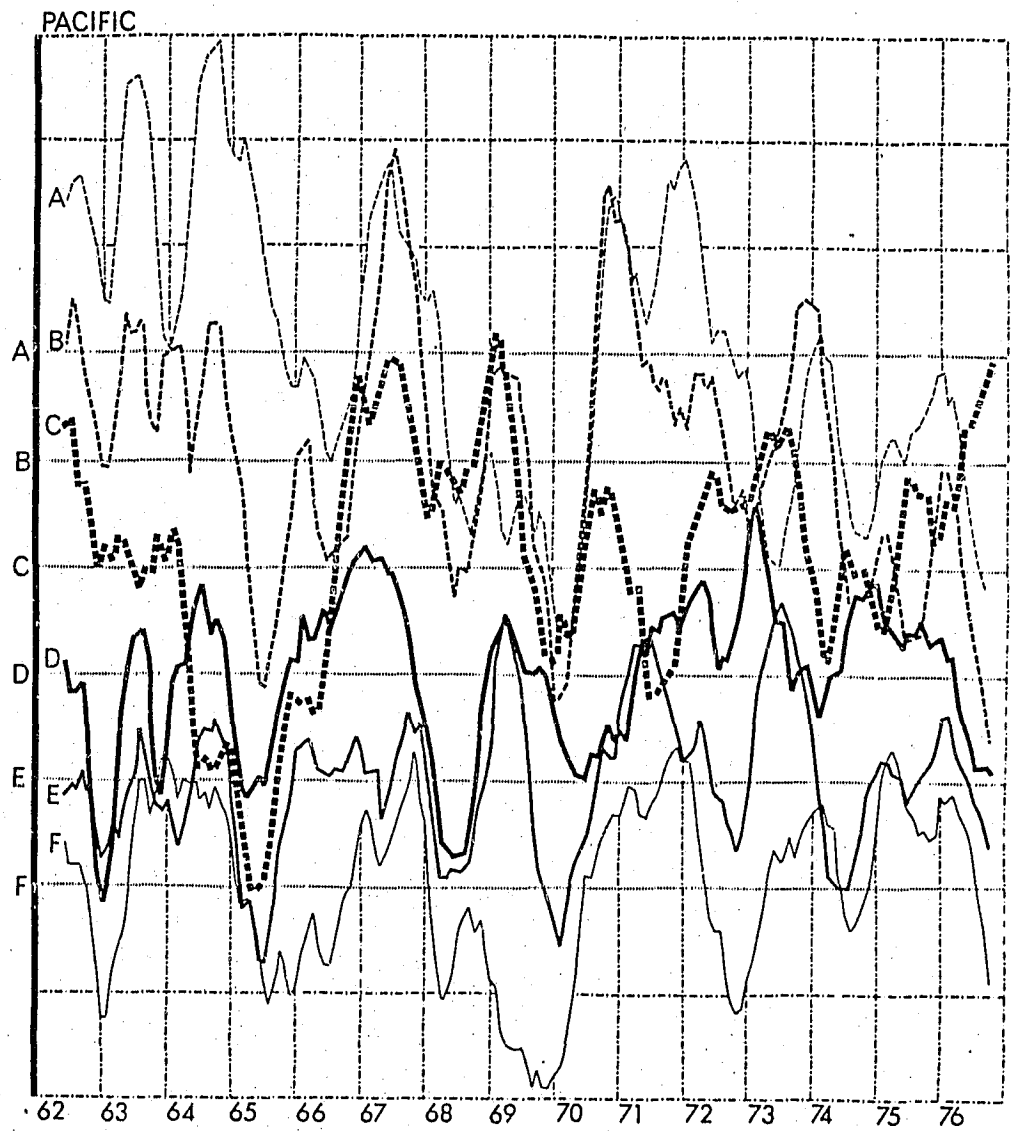

Fig. 8. Monthly SST anomalies (with 7-month running-mean filter applied) in areas defined in Fig. 7. The distance between horizontal dashed-dotted lines conforms to a temperature anomaly of 0.8°C. Dotted lines are reference lines of zero anomalies for areas labelled on the left side of the diagram.

In a previous paper [4] we leave formulated the hypothesis that SST anomalies in the North Pacific are tied to surges in the trade wind systems by a number of feedback mechanisms which are shown schematically in Fig. 9. In Fig. 10 we have plotted the u-component anomalies in the trade-wind regions between 5°N and 19°N, and 1°S to 15°S, and over the longitudinal extent of the Pacific in that latitude belt. Positive anomalies indicate stronger-than-normal easterlies. Positive SST anomalies in Areas D and E observed in 1964, 1966/67, 1969, 1970/71 and 1973 seem to be linked to surges in the trade-wind u-component approximately one year earlier (Fig. 11).

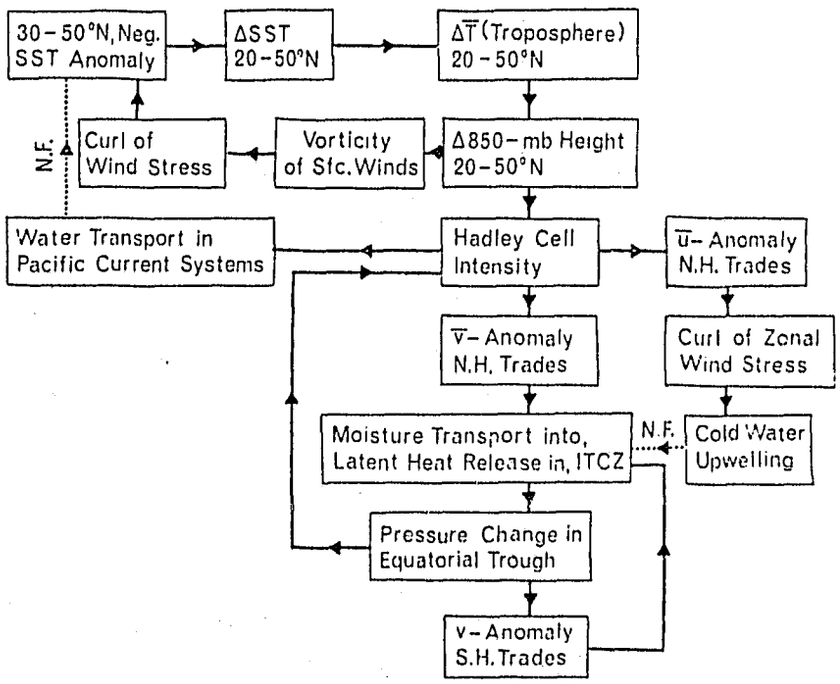

Fig. 9. Schematic diagram of feedback mechanisms involving oceanic and atmospheric anomalies in the Pacific region. Positive feedbacks are indicated by solid lines with arrows between "boxes", negative feedbacks by dotted lines and "NF".

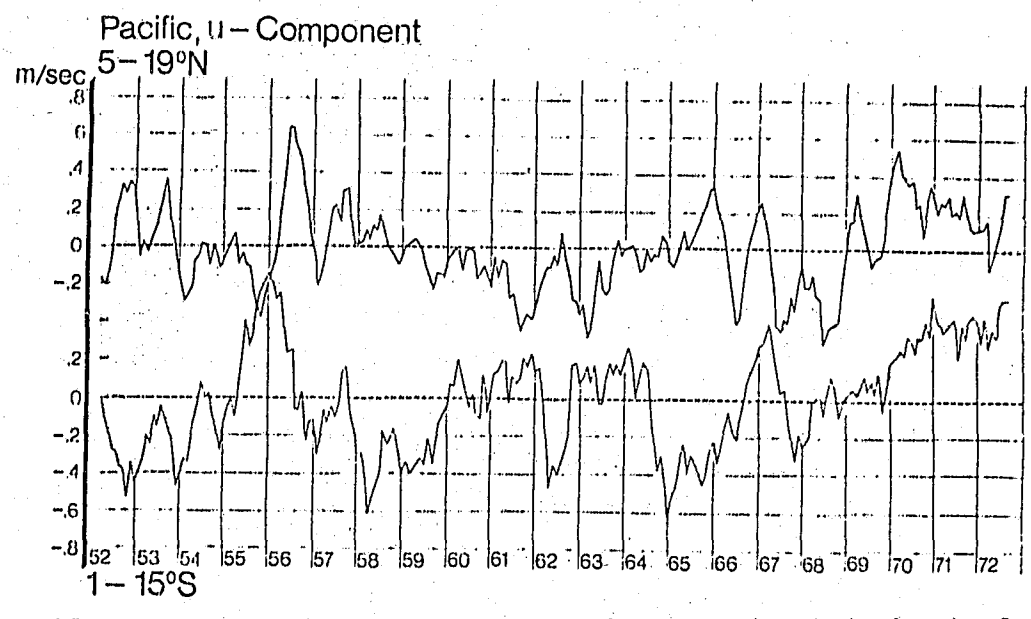

Fig. 10. Monthly anomalies of the u-component of the trade winds in the latitude belts indicated, averaged over the longitudinal extent of the Pacific. A 7-month running-mean filter was applied to the monthly data.

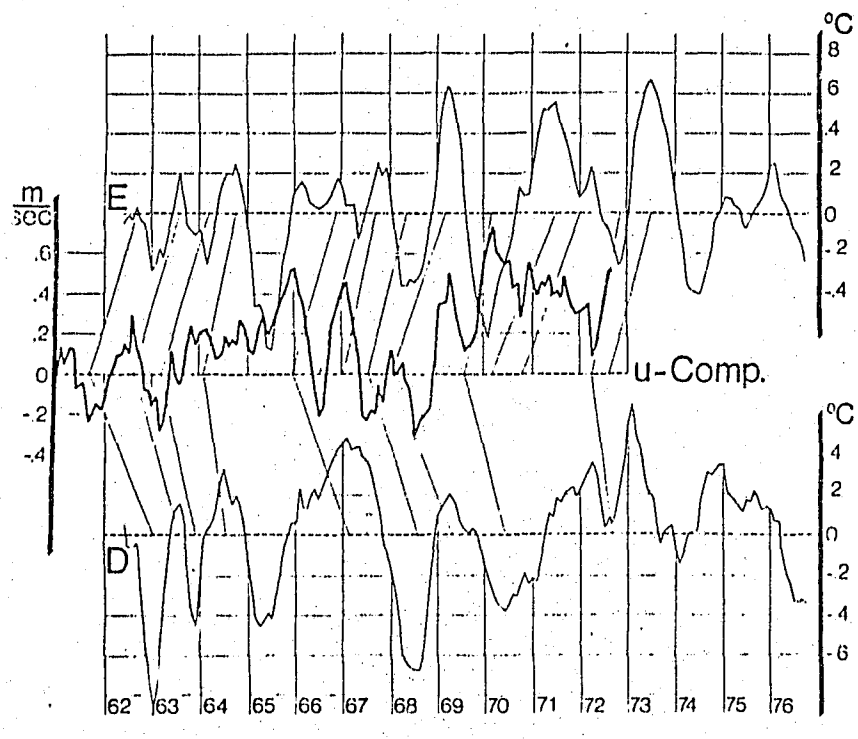

Fig. 11. SST anomalies of Areas E and D in °C (taken from Fig. 8), compared with trade-wind u-component anomalies in the North Pacific in m/sec (taken from Fig. 10). Dotted lines indicate possible time-lagged connections between maximum and minimum values in both sets of curves.

From the foregoing discussion it appears that SST anomalies in the North Pacific are, at least in part, caused by advective processes in the subtropical anticyclonic gyre and in the North Pacific cyclonic gyre. Strong negative temperature anomalies in areas A and F appear to have a particularly pronounced effect on planetary wave patterns [1]. These two regions are affected by water transport in the Kuroshio as well as in the Oyashio. Therefore, feedback mechanisms between ocean and atmosphere have to be considered in low as well as high latitudes.

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