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Part II: Climate Controls

C H A P T E R 3

Northern Hemisphere Climate Change: Physical Processes and Observed Changes

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I. Introduction

Climate changes affect all the components of the climate system in varying degrees, but are manifest through the atmospheric changes. The atmospheric circulation forms the main link between regional changes in wind, temperatures, precipitation, and other climatic variables, and there is also a reasonably strong relationship between some of these even on monthly or longer time scales. These relationships are exploited in preparing long-range (monthly and seasonal) forecasts (Gilman, 1983; Epstein, 1988). In studies of climate variations, internal physical consistency between variables can add confidence to results of analyses of observed changes and thereby help indicate possible causes.

Many studies illustrate the links. Often, relationships are related to particular phenomena, such as the Southern Oscillation (Walker and Bliss, 1932; van Loon and Madden, 1981; Ropelewski and Halpert, 1987, 1989) or the North Atlantic Oscillation (Walker and Bliss, 1932; van Loon and Rogers, 1978; Rogers and van Loon, 1979; Meehl and van Loon, 1979), or to zonal and meridional indices, perhaps as part of an index cycle (Namias, 1950; Lamb and Johnson, 1966; Trenberth, 1976; Salinger, 1980a,b; Makrogiannis *et al.*, 1982).

We now consider the physical reasons why the observed relationships should

exist and go on to examine the observed large-scale multidecadal changes in climate, especially surface temperatures and their links to the circulation, with a special emphasis on insights into observed patterns of change and possible causes. Prospects for the future, with increased greenhouse gases, are also discussed.

II. Physical Reasons for Relationships

Local climates at the same latitude vary considerably around the globe because of the distribution of land and sea, the topography over land, and the associated planetary waves in the atmosphere. Variations in local temperatures on decadal time scales or from year to year are far from uniform but also occur in distinctive large-scale patterns (e.g., Lysgaard, 1949; Petterssen, 1949; Mitchell, 1963; van Loon and Williams, 1976a, 1976b, 1977; Williams and van Loon, 1976; Jones, 1988; Jones *et al.*, 1988; Folland and Parker, 1989); see Fig. 1. The large-scale coherence in these climate variations arises because they are associated with changes in the quasi-stationary planetary waves and other factors, as discussed in the following.

A. Heat Capacity

Generally, the variability of the temperatures over land is a factor of 2 to 6 greater than that over the oceans (Barnett, 1978). In part this can come about because of the formation of strong surface temperature inversions over land in winter, whereas over the oceans surface fluxes of heat into the atmosphere are a major limiting factor. This is really a reflection of the very different heat capacities of the underlying surface and the depth of the layer linked to the surface. The specific heat of dry land is roughly a factor of 4.5 less than that of seawater (for moist land the factor is probably closer to 2). Moreover, heat penetration into land is limited and only the top 2 m or so typically play an active role (as an *e*-folding depth for variations on annual time scales, say). In contrast, convection and wind-induced mechanical mixing within the ocean result in an active mixed layer typically 50 m or so in depth but ranging from less than that during the heating season (spring and early summer) to over 100 m in the fall and winter, when surface cooling helps trigger convection (e.g., Meehl, 1984). These values also vary considerably geographically. Over land, month-to-month persistence in surface temperature anomalies is greatest near bodies of water (van den Dool *et al.*, 1986). Consequently, it is clear that for a given heating anomaly, the response over land should be much greater than over the oceans; the atmospheric winds are the reason why the observed factor is only in the range of 2 to 6.

A further example of this is the contrast between the Northern Hemisphere (NH) (60.7% water) and Southern Hemisphere (SH) (80.9% water) mean annual cycle of surface temperature (Fig. 2). The amplitude of the first harmonic between 40 and 60° latitude ranges from less than 3°C in the SH to about 12°C in the NH. Similarly, from 22.5 to 67.5° latitude, the average lag in temperature response relative to the sun for the annual cycle is 32.9 days in the NH versus 43.5 days in the SH (Trenberth, 1983), again reflecting the difference in thermal inertia. Even the sea surface temperatures (SSTs) in the two hemispheres undergo quite different amplitudes in the annual cycle,

and SSTs are always warmer in the NH than in the SH at each latitude (Shea *et al.*, 1990) (Fig. 3).

At high latitudes over land in winter, there is usually a strong surface temperature inversion whose strength is very sensitive to the amount of stirring in the atmosphere. Such wintertime inversions are also greatly affected by human activities; for instance, an urban heat island effect exceeding 10°C has been observed during strong surface inversion conditions in Fairbanks, Alaska (Weller, 1982). Increases in wind occur with increases in cyclonic activity, usually weakening the inversions and producing much warmer surface temperatures. Cyclonic activity is often accompanied by increases in low-level cloudiness, which also typically acts to warm the high latitudes in winter. Therefore, a modest increase in storminess and wind may produce a large warming in these regions (and conversely, of course, during a decrease in wind) (e.g., Hesselberg and Johannessen, 1958).

An important corollary of the preceding discussion is that changes in surface temperature may bear little relation to changes in heat content, especially in high latitudes over land in winter, where changes may be representative of only a very shallow layer.

It also follows that the oceans will act to delay the onset of any climate change. The heat capacity of the atmosphere corresponds to that of only 3.2 m of the ocean. The seasonal variations in heating penetrate below the mixed layer and on average involve about 90 m of ocean (Meehl, 1984). Using simple models, we can estimate the *e*-folding time for the temperature response to approach equilibrium due to an abrupt change in forcing of the climate (e.g., Ramanathan *et al.*, 1987). The thermal inertia of the 90-m layer would add a delay of about 6 years to the temperature response to a change. The total ocean, with a mean depth of 3800 m, if rapidly mixed would add a delay of 230 years to the response. In reality, the response depends on the rate of ventilation of water through the thermocline. Such mixing is quite uncertain, and an overall estimate of the delay caused by the oceans is 10 to 100 years. The slowest response should be in high latitudes, where deep mixing and convection occur, and the fastest response is expected in the tropics.

B. Planetary Waves

To understand the observed changes it is necessary to understand the changes in planetary waves and teleconnections within the atmosphere. In the NH in winter, the time-mean planetary waves have a strong baroclinic structure and slope westward with height, propagate into the stratosphere, and transport heat and momentum poleward (e.g., Chen and Trenberth, 1988). In particular, from the standpoint of surface climate, changes in the poleward heat transport have a pronounced effect on mean temperatures through changes in local temperature advection (van Loon and Williams, 1977). In other words, anomalous northerly winds often give rise to colder than normal conditions (in the NH), whereas anomalous southerlies are typically warmer than normal. Alternatively, in the NH in winter, winds from the ocean are usually milder while winds from the interior of the high-latitude continents may be considerably colder than normal. In addition, changes in the planetary waves may be

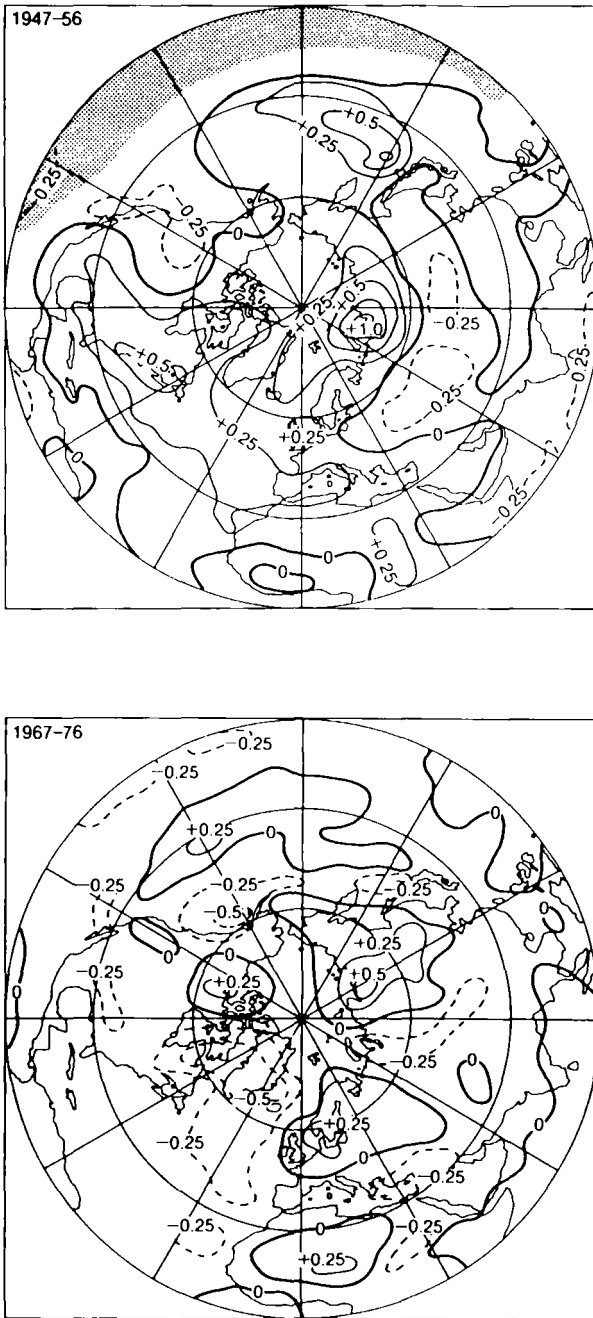


Fig. 1. Decadal average surface temperature or sea surface temperature anomalies as departures from the 1951-1980 mean, for 1947-1956, 1957-1966, 1967-1976, and 1977-1986. Contours every 0.25°C. (From Folland and Parker, 1989; reprinted by permission of Kluwer Academic Publishers.) (*Figure continues.*)

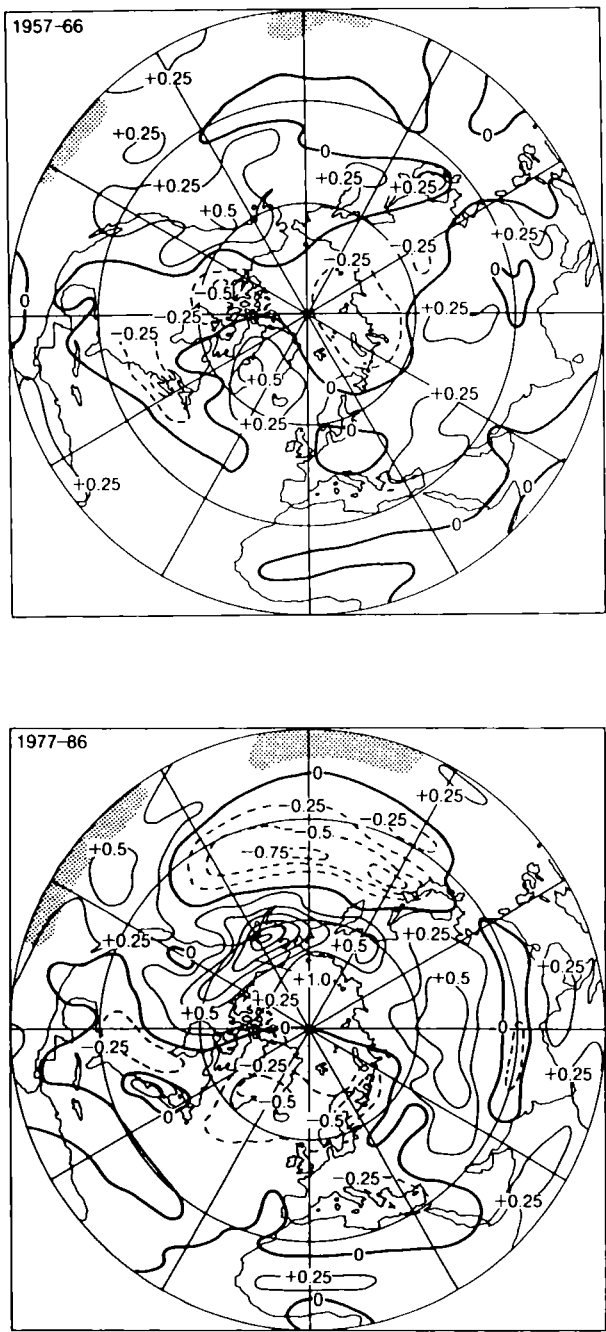


Fig. 1 (Continued)

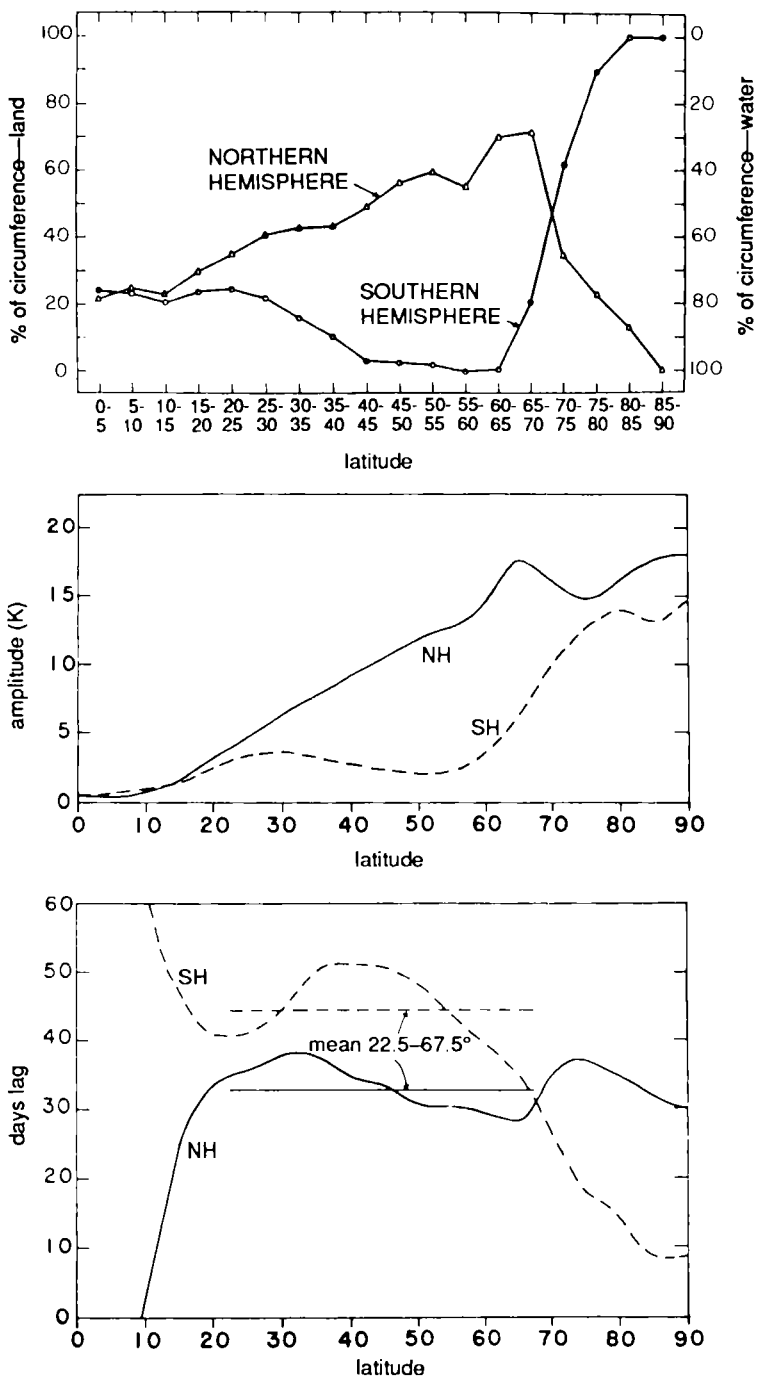


Fig. 2. Zonal averages for each hemisphere of percentage of land around each latitude circle (top); amplitude of the 12-month annual cycle harmonic of surface temperature, °C (center); and phase of the 12-month harmonic of surface temperature in terms of lag behind the sun (bottom). (From Trenberth, 1983; reprinted by permission of the American Meteorological Society.)

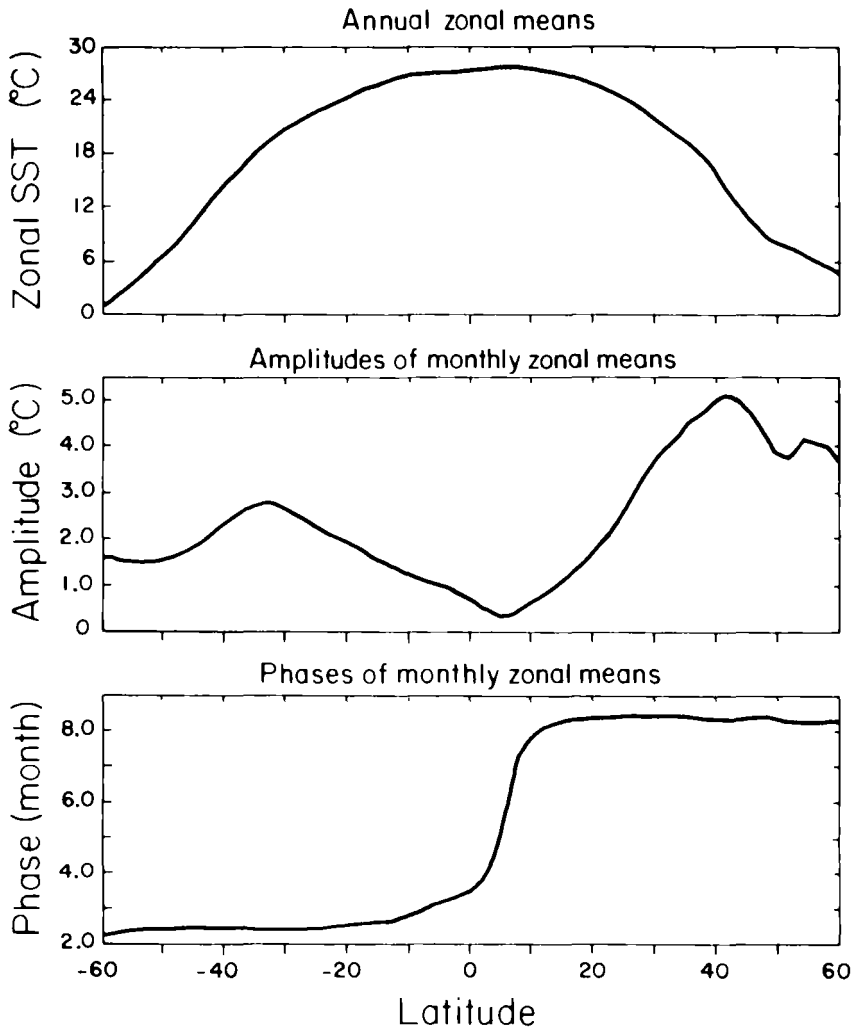


Fig. 3. Zonal average mean sea surface temperatures over the global oceans and zonal average of the amplitude of the annual cycle 12-month harmonic (K). (From Shea *et al.*, 1990.)

associated with periods of persistent blocking in both hemispheres (Namias, 1963; Austin, 1980; Trenberth and Mo, 1985; Trenberth, 1986; Folland, 1983).

In the NH in summer, temperature gradients are much weaker, so changes in winds do not produce much change in advection (van Loon and Williams, 1976b) and local effects become more important. The impact of local solar heating depends greatly on the availability of surface moisture through the partitioning of heat into sensible and latent components. In dry conditions, such as during droughts, more heat goes into raising surface air temperatures, thereby contributing to heat waves. Tren-

berth *et al.* (1988) suggest that this was a significant factor in maintaining the 1988 North American summer drought. It is therefore not surprising to find a highly significant negative correlation between temperature and precipitation totals in most of the United States and Europe in summer (Madden and Williams, 1978). In contrast, in winter the correlations between precipitation and temperature are lower and more patchy, with positive correlations over most of Europe and eastern parts of the United States but with negative correlations over the northern Great Plains of the United States. Positive correlations arise from the dynamical association between warm advection, increased moisture influx, and vertical motion ahead of a trough.

C. Links between the Circulation and Temperatures and Precipitation

It has been implied in the foregoing discussion that temperatures are strongly related to advection in the NH in winter. Strongest advection occurs in the lower troposphere from 850 to 700 mb and is related to that at the surface. Van Loon and Williams (1977) compare 700-mb and surface temperature changes and show, however, that differences exist in trends. Van Loon (1979) and van Loon and Williams (1980) have examined more systematically the relation at 700 mb between heat transports by the stationary planetary waves and transient waves and relationships with temperatures and temperature gradients. Of particular note is the remarkable negative correlation of less than -0.9 for 29 winters between the zonally averaged total poleward heat flux at 45°N and zonal mean temperatures at 40°N . This relationship comes about because of the stationary waves; strong negative correlations extend from 30 to 65°N , showing that *lower temperatures are accompanied by stronger poleward heat fluxes in the stationary waves*. Van Loon (1979) further shows that the transient heat flux varies inversely with the stationary flux and, whereas the transient flux is positively correlated with temperature gradients, as might be expected from baroclinic instability arguments, the total flux is negatively correlated with temperature gradients, implying that the temperature gradients respond to changes in the planetary waves and not the other way around.

The implications of this work have not been sufficiently appreciated. The stationary planetary waves are forced by orography and patterns of diabatic heating arising from the distribution of land and sea, both in the extratropics (Chen and Trenberth, 1988) and in the tropics (Nigam *et al.*, 1988). Therefore, changes in diabatic heating, for instance, can change the planetary waves and associated poleward heat flux (Chen and Trenberth, 1988), with many repercussions. First, reduced heat transports by the planetary waves favor increased temperatures by reducing the effectiveness of the Arctic cold sink in winter. Note that this mechanism does not operate in summer, nor does it work at any time of year in the SH, where heat transports are dominated by the transient component (van Loon, 1979). Consequently, not only the local changes in NH winter temperature (Fig. 1) but also the zonal means and, by extension, the NH mean are greatly influenced by changes in planetary waves.

Second, alterations of the temperature gradients that the transients feed on

through baroclinic instability are accompanied by profound changes in the storm tracks (Trenberth, 1984; Lau, 1988). Storm tracks may be identified by the high-frequency (less than about a week in period) variances in geopotential height in the midtroposphere in both the NH (Blackmon *et al.*, 1977; Lau, 1978, 1979) and SH (Trenberth, 1981, 1982). In this way, the circulation changes may also be systematically linked to changes in precipitation. In addition, the wind accompanying transient disturbances influences the amount of stirring, so the strength of winter surface temperature inversions and probably cloudiness and radiative losses to space would change.

D. Teleconnections

Because of the tendency for atmospheric motions to conserve absolute vorticity, atmospheric motions occur as Rossby waves. Local forcing of such waves sets up a wave train of disturbances and “teleconnections” downstream. In the context of the current topic, teleconnections are important because the anomalies in the circulation and associated temperature and precipitation anomalies may arise from forcing in remote regions. The best-known examples of global impacts of local forcing are changes in SSTs, such as in the El Niño–Southern Oscillation (ENSO) phenomenon, where coupling occurs between the tropical Pacific and higher latitudes via teleconnections. The 1988 North American drought appears to have been one example of this (Trenberth *et al.*, 1988). General circulation modeling experiments have confirmed the causal link between the SST changes and remote atmospheric changes in the winter hemisphere (e.g., Shukla and Wallace, 1983).

E. El Niño–Southern Oscillation Influences

One of the most prominent sources of interannually variability in weather and climate around the world is the ENSO phenomenon. The Southern Oscillation (SO) is a global teleconnection pattern principally consisting of a seesaw (or standing wave) in atmospheric mass involving exchanges of air between the eastern and western hemispheres centered in tropical and subtropical latitudes. The centers of action are located over Indonesia and the tropical South Pacific Ocean. The influence of the SO extends to higher latitudes mostly in wintertime, as wavelike patterns that change the jet stream and storm track locations. El Niño is an anomalous warming of the eastern tropical Pacific Ocean, but in major “Warm Events” the warming extends over much of the tropical Pacific, and in these cases it is clearly linked to changes in the atmosphere, manifested as the SO. The “Cold Events” of the opposite phase are now sometimes referred to as “La Niña.” The El Niño events occur every 2 to 10 years and have far-reaching climatic and economic effects around the world (Fig. 4).

The mechanisms involved are broadly known (Trenberth, 1990b). ENSO results from an interaction between the changes in the tropical Pacific Ocean and the global atmosphere. Surface atmospheric winds drive tropical ocean currents and change the SSTs, which in turn alter the location and strength of atmospheric convection and precipitation in the tropics and so change the atmospheric heating patterns, atmo-

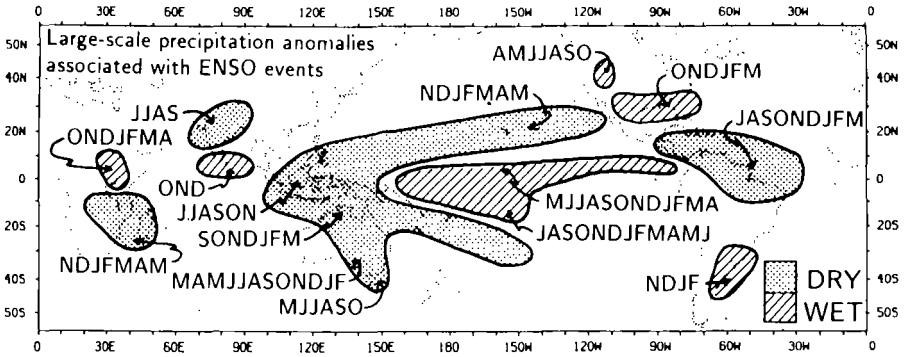


Fig. 4. Schematic of areas influenced by ENSO in terms of precipitation. The months indicated are those affected during the year of and the year following the ENSO event. (Based on Ropelewski and Halpert 1987, 1989; from Trenberth, 1990b.)

spheric waves (teleconnections), and winds in the tropics. It appears that the Pacific Ocean is large enough that the tropical atmosphere and ocean in the Pacific can evolve as a coupled system. Modeling studies reveal that a self-contained irregular oscillation can result (e.g., Zebiak and Cane, 1987).

Although ENSO is a natural part of the earth's climate variations, there are major questions concerning whether the intensity and/or frequency of ENSO events might change as a result of global warming (Trenberth, 1990a). Until recently, climate models used to examine changes due to increased greenhouse effects had such simplified oceans that ENSOs were not included. More recent models are simulating some ENSO-like, but not entirely realistic, variations, but the questions currently remain unanswered.

The observational record reveals that ENSO events have changed in frequency and intensity in the past. Figure 5 shows the Darwin pressure series as one homogeneous index of the SO. High pressures at Darwin coincide with El Niño events (e.g., 1982–1983). The strong SO fluctuations from 1880 to 1920 led to the discovery and naming of the SO (Walker and Bliss, 1932) and strong SO events are clearly evident in recent decades, but a much quieter period occurred from about 1928 to 1950 with the exception of the very strong ENSO of 1939–1942 (Trenberth and Shea, 1987). Quinn *et al.* (1987) have documented ENSO events as seen on the northern west coast of South America for 450 years, and the potential exists for a longer paleorecord based on alluvial deposits in coastal Peru (Wells, 1987) and data from ice cores (Thompson *et al.*, 1984), coral cores (Shen *et al.*, 1987), and tree rings (Michaelsen, 1989).

During ENSO events, the heat stored in the warm pool in the tropical western Pacific is redistributed, resulting in the El Niño itself, and there is a net loss of heat by the ocean to the atmosphere, producing a short period of global warming. Consequently, the warmer individual years in the record of global temperatures are often associated with El Niños. Maxima in global temperatures tend to occur about 6 months after the El Niño itself (Pan and Oort, 1983). 'In one sense, therefore, this

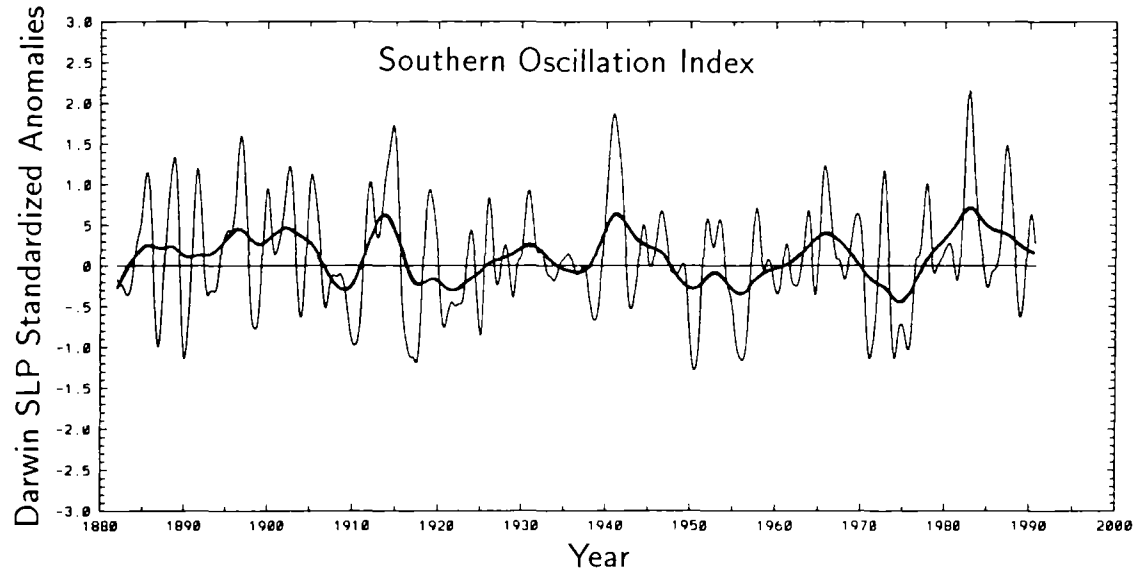


Fig. 5. Darwin sea level pressure anomalies as an index of the Southern Oscillation, beginning in 1882. Values are smoothed to suppress fluctuations less than a year, and the heavy curve shows interdecadal fluctuations. (Updated from Trenberth and Shea, 1987.)

natural variability represents a source of noise and high-frequency variations in global temperatures. It is therefore tempting to use linear regression to remove this noise statistically (Jones, 1989), and the result is certainly a smoother curve for global temperature change, with 20 to 30% of the high-frequency variance removed. However, this would assume that ENSO is not itself influenced by other mechanisms of global climate change, which is unlikely to be the case. Indeed, the fact that several of the warmest years on record in the 1980s were associated with ENSO events implies a reduction of the warming over the past 15 years from other sources because of the imbalance owing to the three sequential Warm Events (1976–1977, 1982–1983, 1986–1987), while there were no strong Cold Events between 1975 and 1988 (see Fig. 5). Because it is not clear how ENSO might change with other climate changes, it seems preferable to retain and acknowledge the ENSO variability in the record.

III. Large-Scale Observed Trends

Low-frequency temperature trends in the NH reveal a rise from about 1890 to 1940 of about 0.5°C , a downward trend until the early 1970s of a few tenths of a degree Celsius, and a further increase in the 1980s (Fig. 6). At any one place in the NH, there

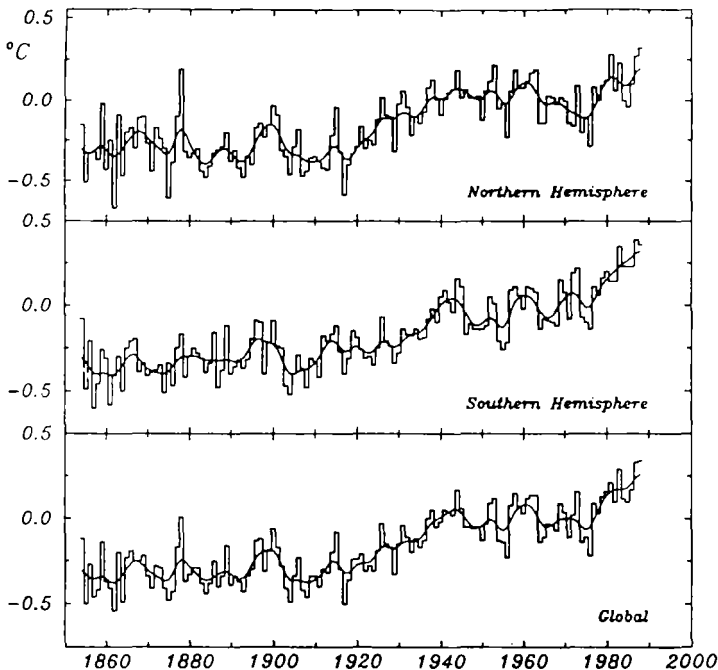


Fig. 6. Annual mean temperatures ($^{\circ}\text{C}$) as departures from 1950–1979 mean. (From P. D. Jones; see Jones *et al.*, 1991.)

are major departures from this time sequence (Fig. 1), although van Loon and Williams (1976a) note that the biggest zonally averaged 15-year trends north of about 50°N exceed the biggest trends elsewhere by more than a factor of 7, so the sign of the hemispheric trends closely follows that of the subpolar and polar regions. Kelly *et al.* (1982) also note the broad similarity between the air temperature trends for the hemisphere and the Arctic (annual correlation 0.81), although with the Arctic variations much greater in magnitude (by a factor of 3 to 4) and more rapid. This amplification in the Arctic is less apparent in the most recent 20 years (Hansen and Lebedeff, 1987).

Of particular note in Fig. 6 in the NH is the fairly abrupt jump in temperatures from about 1920 to 1930, of about 0.3°C for the hemisphere while the increase was 1.1°C for the Arctic. This change has been referred to as a “climatic jump” (Yamamoto *et al.*, 1987). The change is most pronounced in winter but is clearly evident in the other seasons too.

The standard deviations of monthly mean NH surface temperatures in winter are roughly double those in summer, and for the Arctic the winter-to-summer ratio is more than a factor of 3 (Jones and Kelly, 1983). But Jones and Kelly show that individual monthly hemispheric means correlate best with the annual means in summer ($r \sim 0.75$), although correlations are still positive in winter ($r \sim 0.6$), perhaps reflecting larger month-to-month variability in winter. Most studies have focused on wintertime relationships, and the reason for the similarity in trends in all seasons is not clear, although it is probably related to heat storage through anomalies in sea temperatures and sea ice. The latter is strongly linked to circulation and surface temperature, and anomalies persist for up to 6 months (Walsh and Johnson, 1979).

A. The North Atlantic

The hemispheric warming that took place in the 1920s and 1930s was generally regarded by early workers as having resulted from an influx of heat from lower latitudes (Scherhag, 1936, 1939; Lysgaard, 1949). However, several studies have noted that the warming of Europe, which began somewhat earlier than the hemispheric warming, coincided with a period of stronger westerlies from about 1900 to 1938 (Lamb and Johnson, 1966; Lamb, 1972; Makrogianis *et al.*, 1982; Parker and Folland, 1988), so that, especially in winter, there was an absence of very cold outbreaks. Rogers (1985) has noted that the best correlation between European temperatures and wind is with the westerly component, reflecting whether or not the encroaching air masses have had an oceanic moderating influence imposed.

Variations in the meridional pressure gradient across the North Atlantic from 40 to 60°N are associated with pronounced changes in the Icelandic Low. Such changes are strongly tied to the North Atlantic Oscillation (van Loon and Rogers, 1978). However, van Loon and Rogers show that there is a seesaw in winter temperatures between Greenland and northern Europe associated with this mode, whereby, most of the time, above-normal temperatures in Europe go hand in hand with below-normal temperatures in Greenland and the Canadian Arctic (referred to as GB, Greenland below), and vice versa (GA, Greenland above). Warm winter weather in

Europe goes along with a deeper Icelandic Low and a stronger Azores high, with a greatly enhanced westerly wind flow onto Europe. In Greenland, however, the reversals in temperature anomalies are associated with the meridional wind (Rogers, 1985).

This seesaw in temperatures has strong canceling effects for the Arctic as a whole and does not account for the Arctic warming of the 1920s. [Any cancellation of temperature anomalies presumes that there is adequate data coverage to resolve the opposite anomalies properly. Kelly *et al.* (1982) show that much of the Canadian Arctic and northern Greenland could not be analyzed until after 1935, whereas data were available before 1895 for northern Europe and the southern half of Greenland.] Van Loon and Rogers (1978) show that there were nine Januaries with Greenland below and Europe above normal by at least 4°C (GB) but only two with Greenland above and Europe below normal (GA) from 1900 to 1925, whereas the overall incidence of the two types is about equal. Iceland (Einarsson, 1984) and Spitzbergen began to warm after about 1917 (see Hesselberg and Johannessen, 1958), whereas Greenland and northern Canada warmed in the mid-1920s (Kelly *et al.*, 1982; Rogers, 1985). For the entire Arctic to warm, it seems necessary for both Greenland and Europe to be warm (see Jones and Kelly, 1983), cases considered by van Loon and Rogers (1978) as “both above” (BA), in contrast to the seesaw conditions. From 1926 to 1939, van Loon and Rogers found eight BA Januaries versus two GA and four GB cases and compared with only one January in this class from 1900 to 1925 (Fig. 7).

Sea level pressure composites for the “both above” versus “both below” cases (Fig. 8) (van Loon and Rogers, 1978) reveal higher than normal pressures over the Atlantic south of 55°N and a broad region of lower than normal pressures throughout the Arctic, so that there is a stronger westerly flow onto Europe but an absence of strong meridional flow anywhere from the polar regions. Van Loon and Madden (1983) show that the time of much colder mean temperatures (see Fig. 6), 1901 to 1916, was remarkable in the North Atlantic for the very low standard deviations of monthly mean sea level pressures north of 55°N, implying that there was less variability. In contrast, lower pressures in the Arctic (e.g., Fig. 8) are accompanied by an increased number of cyclonic disturbances (Rogers and van Loon, 1979) that increase stirring and cloudiness and thus break up the shallow surface temperature inversions in winter.

We conclude, therefore, that during the Greenland–northern Europe seesaw in temperatures the location of cold advection out of the Arctic is changed to affect principally either Greenland or Europe. We infer that for both Greenland and northern Europe to be above normal in temperature, the circulation is more zonal, there is less mean meridional flow out of the Arctic, there are fewer cold outbreaks anywhere, but there is increased transient cyclonic activity in the Arctic.

The relationship is not altogether straightforward, as pointed out by van Loon and Williams (1977), because of differences between what happens at the surface and at 700 mb. For the period 1949 to 1972, they show that when winter zonal mean 700-mb temperatures were generally decreasing but with a maximum cooling at 45°N, surface temperature trends were also down but with maximum cooling in the

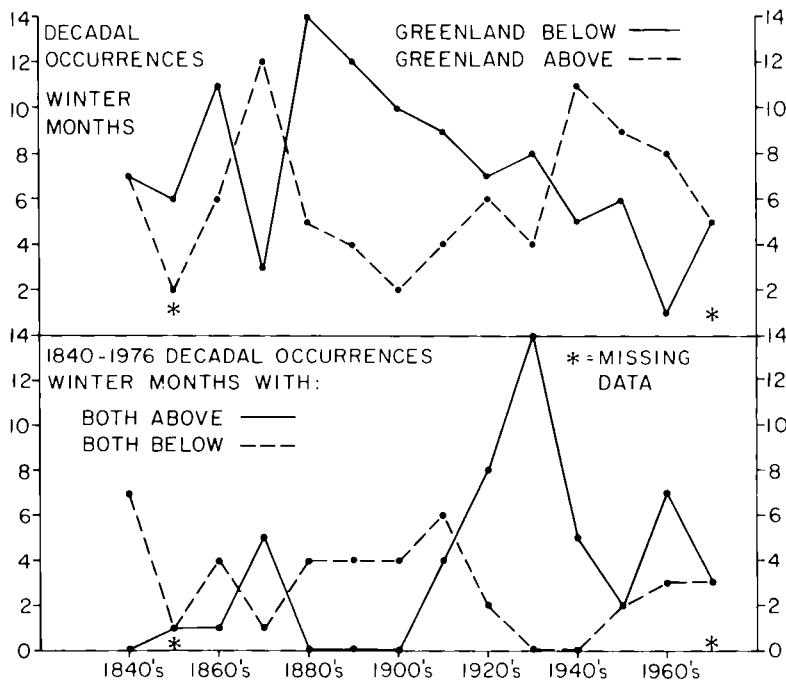


Fig. 7. Number of cases per decade of the four temperature categories Greenland above (northern Europe below), Greenland below, both above, and both below for the northern winter (December, January, February). (From van Loon and Rogers, 1978.)

Arctic. Because there was enhanced poleward heat flux at 700 mb during this trend, thereby cooling midlatitudes, one might expect a compensating warming from this source at high latitudes. Such a warming is not found, evidently because of higher pressures in the Arctic and the associated shifts in storm tracks to lower latitudes following the changes in temperature gradients; see discussion in Section 2c.

Several studies provide clues about possible teleconnections and causes for changes in the North Atlantic. Rogers and van Loon (1979) and Meehl and van Loon (1979) have described associations of the seesaw in temperatures between Greenland and northern Europe and various other variables that may be relevant in determining causes. Because of changes in the location of the Intertropical Convergence Zone (ITCZ) in January, there are changes in rainfall over southern Africa between the two modes of the seesaw, but not in other circulation types (Meehl and van Loon, 1979). Moreover, anomalies in SSTs and sea ice develop locally, but significant SST anomalies in the tropical Atlantic are also associated with the seesaw. Ratcliffe and Murray (1970) and Palmer and Sun (1985) have associated changes in pressures over the North Atlantic and Europe with SSTs in an area near Newfoundland, and Palmer and Sun performed a modeling study with specified SST anomalies in the northwest Atlantic which produced results that compared well with the observations. Rowntree

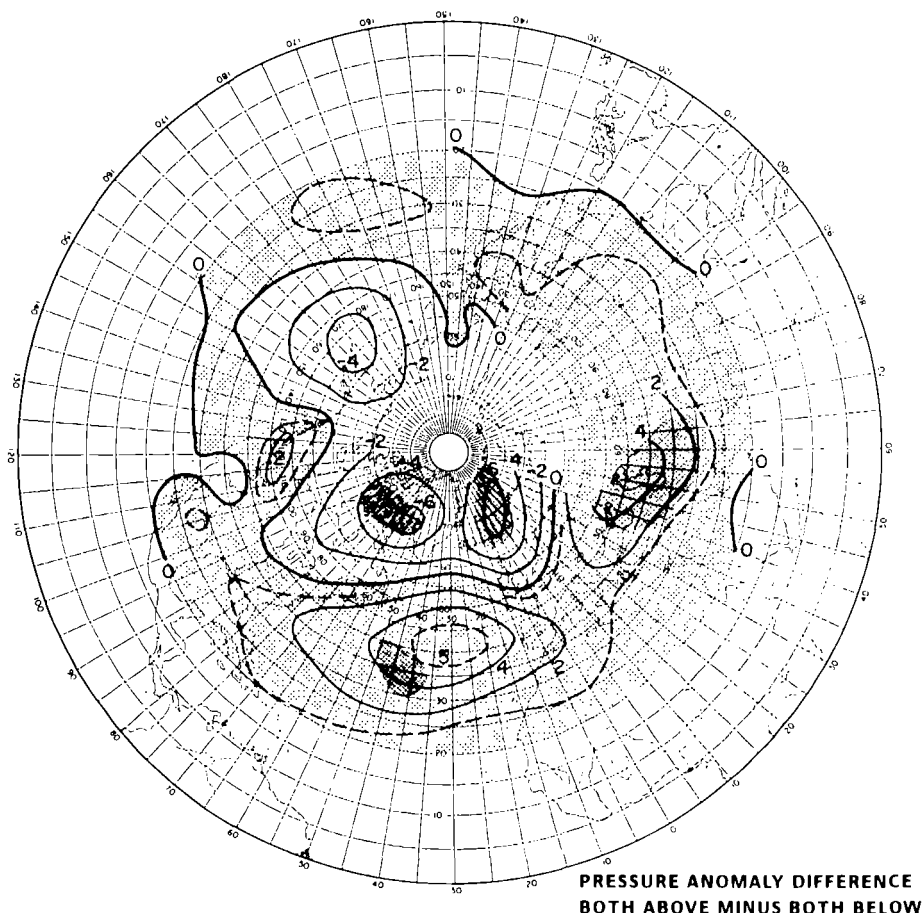


Fig. 8. Difference in pressure anomalies between January months when temperatures at Jakobshavn (Greenland) and Oslo (Norway) were both above and those when they were both below normal (mb). The dark shading indicates 5% significance. (From van Loon and Rogers, 1978; note: the original published figure stated incorrectly that it was for "both below minus both above.")

(1976) pursued the possibility that observed above-normal SSTs in the tropical North Atlantic helped to maintain the blocked, cold 1962–1963 winter in northern Europe using both observations and modeling and was able to show some promising, although not conclusive; support for this idea. Folland *et al.* (1986) have similarly used observed changes in SST extending over almost the entire global oceans in a climate model to show that they were a likely factor in circulation changes that led to the prolonged Sahel drought that began after the 1950s. Lau and Nath (1990) analyzed atmospheric responses to specified global SSTs in an atmospheric climate model and found North Atlantic and northern Europe changes to be strongly influenced by SSTs off Newfoundland and in the tropical South Atlantic.

B. The North Pacific

Van Loon and Rogers show that going along with the Greenland–Europe seesaw in temperatures is a distinctive pattern over North America whereby GB cases correspond to colder conditions in Alaska and along the West Coast but warmer than normal conditions over the eastern three-quarters of North America south of about 55°N. Temperatures in western North America appear better related to changes in the North Pacific and the strength of the Aleutian Low; however for the GA versus GB winters, van Loon and Rogers show a link between a weaker Aleutian Low and a stronger Icelandic Low. Namias (1970, 1972) and Dickson and Namias (1976) have noted the out-of-phase relationship in temperature anomalies across North America during the 1960s, when the east was colder and the west warmer than usual.

Examination of Fig. 1 for the decadal mean changes in temperatures shows an alternation in the Pacific, between cooling along the west coast of North America and Alaska from 1947 to 1956 and 1967 to 1976 and warming in the western or central Pacific, and vice versa from 1957 to 1966 and especially 1977 to 1986. Figure 9 shows time series of Pacific mean sea level pressure for the winter period November to March, averaged from 27.5 to 72.5°N, 147.5°E to 122.5°W, or virtually the entire North Pacific (from Trenberth, 1990a). This index is closely related to changes in the intensity of the Aleutian Low and is fairly strongly tied to the Pacific–North American (PNA) teleconnection pattern [see Wallace and Gutzler (1981), who show that the surface signature of the PNA is mostly confined to the Pacific in the area selected for Fig. 9]. This reveals a huge decrease in the pressures in the Aleutian Low for 1977 to 1988, with pressures lower by 2.0 mb averaged over the vast area of the North

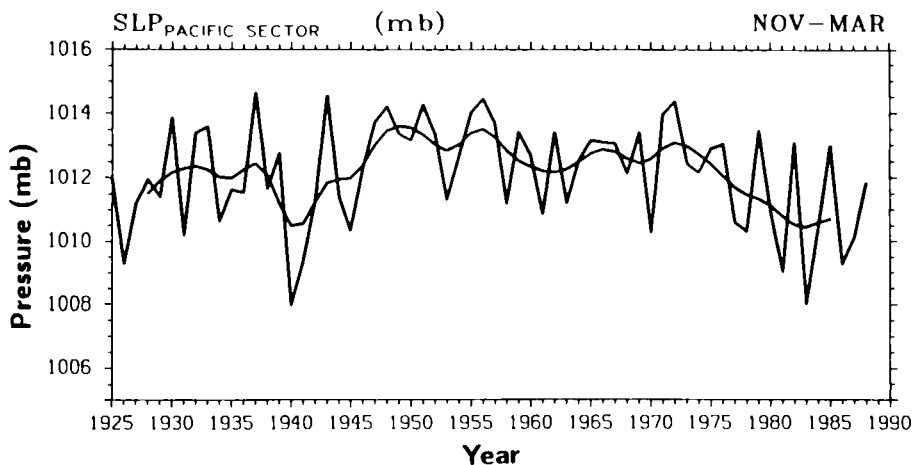


Fig. 9. Time series of mean North Pacific sea level pressures averaged over 27.5 to 72.5°N, 147.5°E to 122.5°W for the months November through March. A low-pass filter has been used to show decadal trends. (From Trenberth, 1990a.)

Pacific. These differences are present in all five winter months and are highly statistically significant (Trenberth, 1990a). They correspond to the center of the low farther east and deeper by 4.3 mb for the five winter months and deeper by 7 to 9 mb in January. A new climatology for surface wind stress based on 1980–1986 (Trenberth, 1991) revealed changes from previous climatologies that confirm the reality of the sea level pressure changes (Trenberth, 1990a). It is also consistent with and provides a partial explanation for the very large regional Pacific temperature anomalies for 1977–1986 in Fig. 1, with warming of over 1.5°C in Alaska and cooling of more than 0.75°C in the central and western North Pacific, as would be expected in association with a stronger Aleutian Low from considerations of thermal advection and increased ocean mixing.

When possible causes of changes and teleconnections are considered for the North Pacific, one prospect is *in situ* forcing. The question of the role of extratropical SST anomalies in the North Pacific and their influence on the circulation is pursued vigorously by Namias in a series of articles (e.g., Namias 1959, 1963) and by Wallace *et al.* (1990) and Lau and Nath (1990). Although it is likely that there is an effect, it probably depends greatly on the synoptic situation and other influences (as noted later) as well, so definitive answers do not yet exist. Also, insofar as the effects on planetary waves are concerned, enhanced land–sea contrasts would be needed to give a deeper Aleutian Low, whereas the observations show that the latter was accompanied by below-normal SSTs.

It is much more likely that the North Pacific changes are linked to interdecadal changes in the tropics (Trenberth, 1990a). In the NH winter, modeling results confirm that the observed deeper Aleutian Low during El Niño events is part of the teleconnection response to warmer tropical Pacific SSTs. In the 1977–1988 period both the tropical Pacific and tropical Indian Ocean had above normal SSTs (Nitta and Yamada, 1989). In the Pacific there were no strong Cold Events but several Warm Events (El Niños) (see Fig. 5). Whether this can be ascribed to any cause or is merely a part of natural variability is a very difficult question.

IV. Future Prospects: Links with the Greenhouse Effect

As well as all of the internal physical processes that we have discussed so far, several processes external to the climate system are known to be changing in ways that should affect climate. Although variations in solar activity are observed, the impact on the climate system is not known and is mostly thought to be small. The main external process of note in this context is the gradual buildup of several greenhouse gases, notably carbon dioxide, methane, nitrous oxide, and the chlorofluorocarbons (CFCs), due to human activities (IPCC, 1990). Because these gases become well mixed in relatively short times, they are globally distributed and the increases will undoubtedly cause climate change. The questions then are what form the climate change will take, how quickly it will happen, and how much will happen. One of the main prospects is for global warming.

There is considerable pressure on climate modelers to make projections into the future, and they have done so. In interpreting their results, however, it must be borne in mind that the models are far from perfect. In surveying the modeling results, looking for common features and assessing the reliability of different models (see IPCC, 1990), the following assessment of likely climate change due to increased greenhouse gases is made:

1. The models indicate global warming of 2 to 5°C for an equilibrium climate with doubled CO₂. Effective doubling of CO₂, taking into account the other greenhouse gases too, is likely around 2030 to 2050 with corresponding manifestations of Northern Hemisphere climate change occurring 20 to 30 years later (see Section 2a). The lag is likely to be greater over the SH; see Fig. 10 (Stouffer *et al.*, 1989). Over the past century, during which carbon dioxide has increased from 280 to 350 parts per million by volume (25% increase), the observed temperature increase has been fairly modest, about 0.5°C; see Fig. 6. Because of this and because of uncertainties in the models, particularly the role of clouds, it appears that the best estimate of future warming is at the low end of the values predicted in the climate models, perhaps 2 to 3°C for effective doubling of CO₂. The larger values do not appear to be tenable unless the oceans are playing tricks on us. Moreover, a big factor in producing the

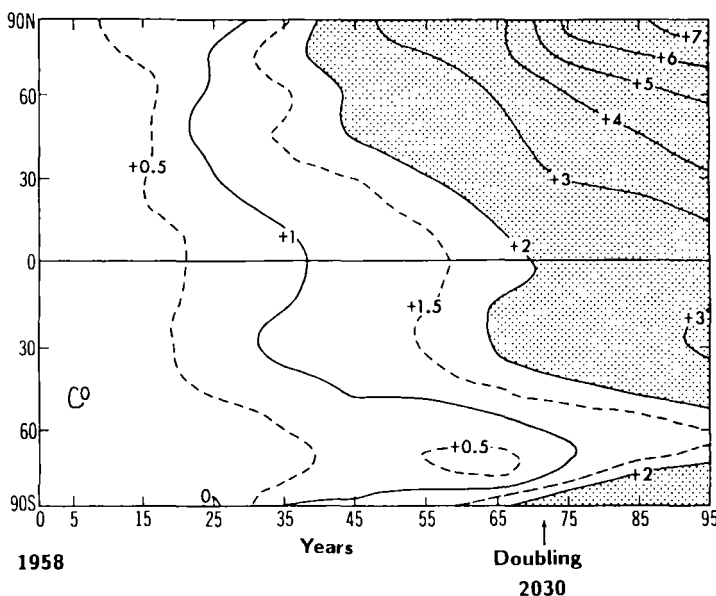


Fig. 10. Latitude–time section of the difference in zonally averaged decadal mean surface air temperature (°C) between a climate model run with CO₂ increasing at 1% per year (compounded) and a control run with constant CO₂. (Adapted from Stouffer *et al.*, 1989.)

larger values is positive feedback in clouds, which is not proved. Nevertheless, the error bars are significant.

2. The hydrological cycle is likely to speed up by about 10% with CO₂ doubling, giving increased evaporation and increased rainfall in general. Because more precipitation is apt to fall as rain in winter and there would be faster snowmelt in spring, soil moisture availability going into summer over midlatitude continents is likely to be less. Combined with increased evapotranspiration in summer, this implies that any natural tendency for a drought to occur is likely to be enhanced. However, there is not good agreement among the models on this aspect. Increases in rainfall in winter but drier conditions in summer imply that water management will become a prominent issue in the future.

3. Because warming results in expansion of the ocean and melt of snow and glacial ice, one real threat is a rise in sea level. However, there may be some compensation through increased snowfall on top of the major ice caps (Greenland and Antarctica), so they could increase in height even as they melt around the edges. Current rises in sea level of 1 to 2 mm/year are observed, and this should increase, but the main impacts will probably be felt much later next century.

4. Increases in water vapor (a greenhouse gas) and decreases in snow cover and sea ice (lower albedo) with warming provide positive feedbacks that should enhance the effects as time goes on. One result of this is that largest warming should occur in the Arctic.

5. Stratospheric cooling is another likely effect of increased greenhouse gases, and this has important implications for ozone because the kind of heterogeneous chemistry responsible for the Antarctic ozone hole is more effective at lower temperatures. The CFCs that are responsible for the ozone hole are also greenhouse gases.

6. Another possibility, because of increased SSTs, is increased frequency and/or increased intensity of tropical storms and hurricanes. This is because SSTs above about 27°C are needed before hurricanes can sustain themselves by feeding on the extra water vapor and thus latent heat available in such regions.

7. Greatest confidence exists on the global scale; regional climate changes are much more uncertain.

8. Coupled ocean–atmosphere general circulation models used to make projections have only very recently been able to simulate, as part of the overall variability within the model, very rudimentary ENSO cycles. Only one study exists so far of the possible effects on ENSO of climate change associated with the increasing greenhouse gases. It does not address the possible changes in frequency and magnitude of events; much longer model runs would be needed. However, it does find that ENSOs continue to exist in a warmer world (G. A. Meehl, personal communication, 1990). Because El Niños and La Niñas have the effect of creating droughts and floods in different parts of the world (Fig. 4) and global warming tends to enhance the hydrological cycle, there is a real prospect that future such events will be accompanied by more severe droughts and floods. In the tropics, in particular, because of the great dependence on rainfall and its tendency to fall at certain times of the year

(the dry season, the wet or monsoon season), the main prospect that looms is one of larger variability and larger extremes in weather events.

It is clear that natural variations are capable of producing low-frequency fluctuations in the climate system through the long-term memory of the ocean. In the case of the El Niño–Southern Oscillation, a self-contained low-frequency oscillation can result. Because the ocean is simultaneously affected by many climate forcings, including increasing greenhouse gases, there is great difficulty in separating out the real cause of any observed change. Indeed, generally multiple forcings will contribute to any observed change in differing amounts.

From the perspective of changes in the atmosphere, it may be possible to attribute a particular change in surface temperatures and circulation to SST anomalies, but this does not necessarily rule out other external mechanisms. In that case, it simply changes the focus of the question to the origin of the changes in SSTs. Because it is clear that changes in temperatures are not uniform over the globe, but rather contain considerable large-scale coherent structure with regions of opposite sign (Fig. 1), it is vital to establish the linkages between changes in circulation and temperatures and precipitation to build up understanding of the climate changes. Inevitably, all the different factors involved will complicate any interpretation of surface temperature changes in terms of global warming.

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Children of the Tropics: El Niño and La Niña

Bob Henson, NCAR Information and Education Outreach Program
Kevin Trenberth, NCAR Climate and Global Dynamics Division

For many years, coastal residents of Peru had noticed a strange feature of the eastern Pacific Ocean waters that border their home. This region of tropical yet relatively cool water is host to one of the world's most productive fisheries and a large bird population. In the first months of each year, a warm southward current usually modified the cool waters. But every few years, this warming started early (in December), was far stronger, and lasted as long as a year or two. Torrential rains fell on the arid land; as one early observer put it, "the desert becomes a garden." Warm waters flowing south brought water snakes, bananas, and coconuts from equatorial rain forests. However, the same current shut off the deeper, cooler waters that are crucial to sustaining the region's marine life.

This is El Niño, "the Christ child," so named because of its frequent late-December appearance. Once thought to affect only a narrow strip of water off Peru, it is now recognized as a large-scale oceanic warming that affects most of the tropical Pacific. The meteorological effects related to El Niño and its counterpart, La Niña (a cooling of the eastern tropical Pacific), extend throughout the Pacific Rim to eastern Africa and beyond.



Among the many global phenomena connected to the El Niño–Southern Oscillation (ENSO) are Asian monsoons. The migration of the monsoon each year has been linked to the tropical Pacific rainfall patterns that are part of ENSO.

El Niño is normally accompanied by a change in atmospheric circulation called the Southern Oscillation. Together, the ENSO (El Niño–Southern Oscillation) phenomenon is one of the main sources of interannual variability in weather and climate around the world. Since recognizing some 25 years ago that the oceanic and

atmospheric parts of ENSO are strongly linked, scientists have moved steadily toward a deeper understanding of ENSO. Climate forecasters have taken the first steps toward predicting the onset of El Niño and La Niña events months in advance. Still, much remains to be learned about these children of the tropics.

The basics of ENSO

It was the atmospheric part of ENSO—the Southern Oscillation, or SO—that first attracted the attention of scientists. Sir Albert Walker documented and named the SO in the 1930s. Other persistent patterns of high and low pressure had been previously noted in the North Pacific and North Atlantic; thus, the “southern” in SO.

The clearest sign of the SO is the inverse relationship between surface air pressure at two sites: Darwin, Australia, and the South Pacific island of Tahiti. As seen in Figure 1 below, high pressure at

one site is almost always concurrent with low pressure at the other, and vice versa. The pattern reverses every few years. It represents a standing wave or “see-saw”—a mass of air oscillating back and forth across the International Date Line in the tropics and subtropics.

This one-dimensional picture was extended vertically by renowned meteorologist Jacob Bjerknes in 1969. He noted that trade winds across the tropical Pacific flow from east to west. To complete the loop, he theorized, air must rise above the western Pacific, flow back east

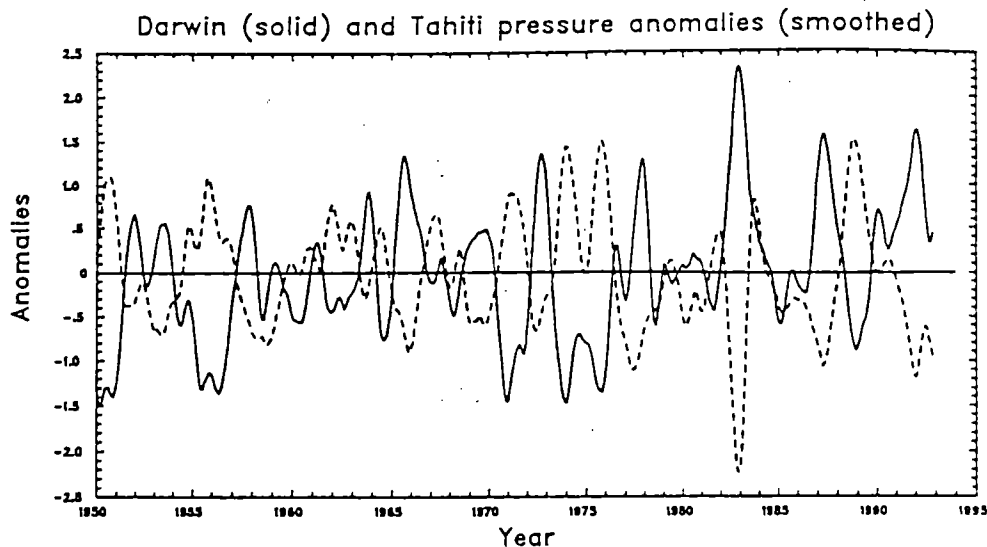


Figure 1: This time series of sea-level pressure anomalies at Darwin, Australia (solid), and Tahiti (dashed) from 1950 through 1992 is smoothed to remove fluctuations on time scales of less than a year. It shows the inverse relationship in pressure patterns between the two sites.

at high altitudes, then descend over the eastern Pacific. Bjerknes called this the Walker circulation (in honor of Sir Albert); he also was the first to recognize that it was intimately connected to the oceanic changes of El Niño and La Niña.

The persistent easterly trade winds are a key ingredient in the ENSO process. They have two major effects:

- Pushing water toward the western Pacific. The sea level in the Philippines is normally about 60 centimeters (23 inches) higher than the sea level on the southern coast of Panama.
- Allowing the westward-flowing water to remain near the surface and gradually heat. This gives the water's destination—the western Pacific—the warmest ocean surface on earth. Usually above 28°C (82°F), parts of this pool are sometimes as warm as 31.5°C (89°F).

As warm surface water collects in the western Pacific, it tends to push down the thermocline, the boundary separating well-mixed surface waters from deeper, colder waters. The thermocline is usually about 40 meters (130 feet) deep in the eastern Pacific but varies from 100 to 200 meters (330–660 feet) deep in the west. (See Figure 2).

The persistent oceanic heat surrounding Indonesia and other western-Pacific islands leads to frequent thunderstorms and some of the heaviest rainfall on earth. The rainfall is abetted by the upward motion produced by the Walker circulation. The distribution of sea-surface temperatures (SSTs) drives the enhanced rainfall, Walker circulation, and associated trade winds, which in turn are responsible for the ocean currents and the distribution of SSTs. The atmosphere drives the ocean and the ocean drives the atmosphere in a truly coupled mode of behavior.

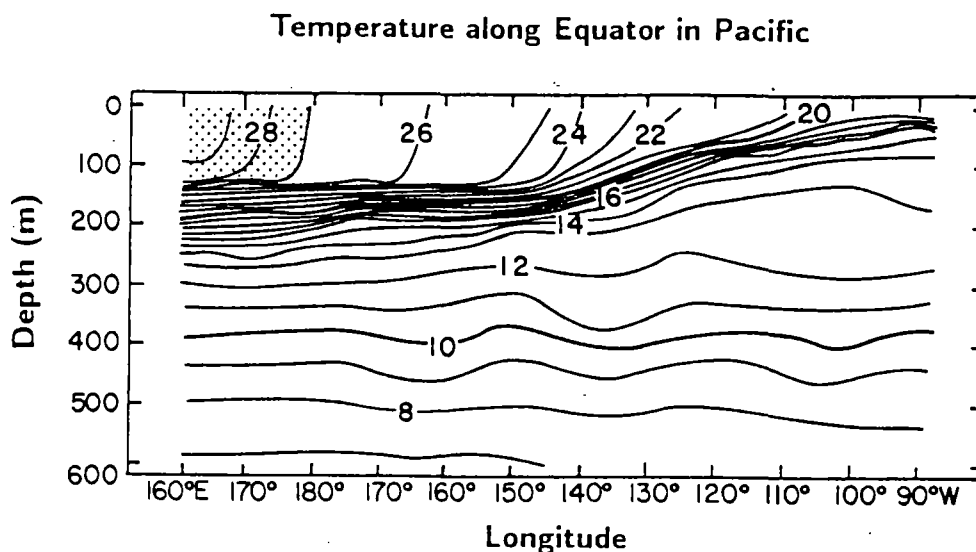


Figure 2: This cross-section of the Pacific Ocean along the equator shows depth in meters and ocean temperatures in degrees Centigrade. The sloping of the thermocline that separates warm and cool waters is clearly visible.

Anatomy of El Niño

The sea-level pressure at Darwin can be used as an index of the SO and, by extension, as a guide to the major ENSO events of the past.

Figure 3 below shows the Darwin pressure anomalies (deviations above or below normal) of the past century, smoothed to eliminate short-term effects. Positive anomalies correspond to El Niño events, negative anomalies to La Niña. Note that

- El Niño and La Niña events tend to alternate about every two years.

However, the time from one event to the next can vary from one to ten years.

- The strength of the events, as judged by the pressure anomaly, varies greatly from case to case. The strongest El Niño in this record occurred in 1982–83. (Its effects included torrential storms throughout the southwest United States and Australia's worst drought this century. See Figure 4 below for other world impacts from this event.)

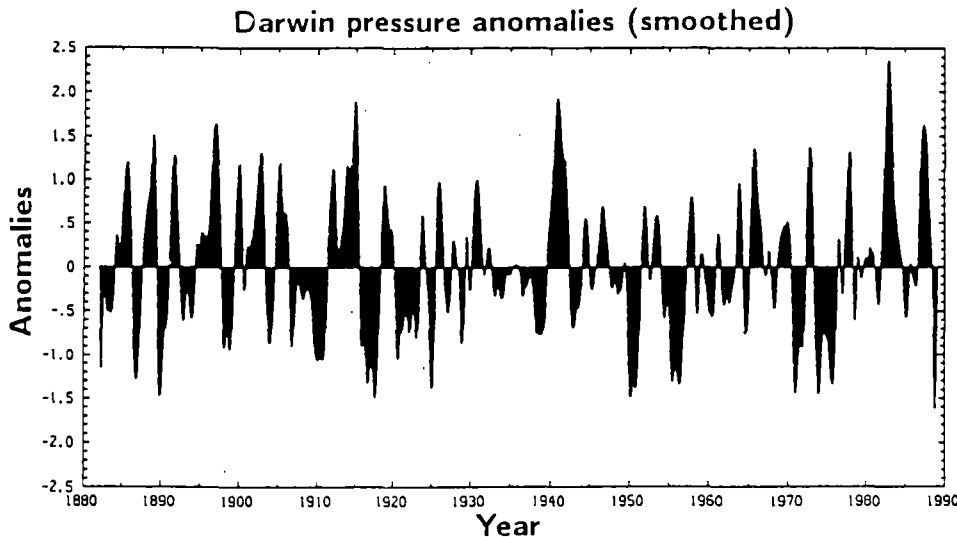
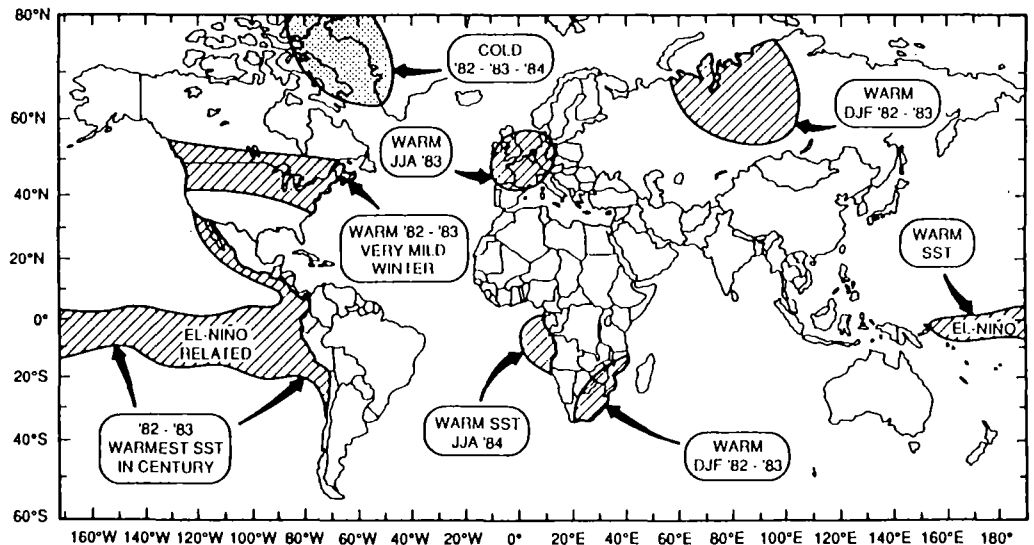


Figure 3: Pressure anomalies at Darwin (in millibars) show the ebb and flow of ENSO over the past century. Positive anomalies occur with El Niño and negative anomalies with La Niña.

Figure 4: The widespread impact of the 1982–83 El Niño is evident in this portrayal of extreme temperature events from 1982 to 1984. Months are grouped by their first initials (for instance, JJA is "June-July-August"). SST denotes sea-surface temperature.



- Sometimes El Niño and La Niña events are separated not by their counterparts, but by rather normal conditions.

Figure 3 and other evidence like it reveal that ENSO is a periodic yet highly variable phenomenon. Sometimes the warm waters generated by an El Niño flow all the way across the Pacific. The 1982–83 event increased surface water temperatures near Peru by up to 4°C (7°F). In the much weaker event of 1986–87, the warm water flowed eastward only as far as the mid-Pacific (near 170°W) and raised the temperatures there a modest 1°C (1.8°F) or so. In still other cases, warm anomalies first appear offshore of Peru and then progress westward to meet the preexisting warm pool.

Bjerknes was unable to determine why the SO reverses or why the ENSO changes from warm to cold conditions (El Niño to La Niña). This is still a subject of intense research. Although the atmosphere and ocean act in harmony after an ENSO event begins, some intriguing questions remain. What sets the system off? Is there really a self-sustained cycle in the atmosphere-ocean system? What is the role of other influences?

Recent work using computer models of ENSO hints that the storage of heat throughout the tropical ocean is a key element. Apparently, as rainfall is reduced

in La Niña, the increased solar input heats up the ocean, especially in the deep western-Pacific warm pool. During El Niño, heat is transported from the tropics to higher latitudes by ocean currents, and additional heat goes to the atmosphere, mainly through evaporation. Global temperature averages can reflect this heat input, rising by as much as 0.3°C (0.5°F) in the months after a strong ENSO event. Thus, the tropical Pacific Ocean loses heat during El Niño and gains it during La Niña.

Could it be the length of time needed to “recharge” the ocean with heat that determines when ENSO events start and stop? Some model results point in this direction. However, conditions outside the tropics also seem to be important. Atmospheric changes over the South Pacific Ocean often precede SO changes by one to three seasons. Some studies have related the onset of El Niño to anomalous snowfall over Asia and to the southeast Asian monsoon. Wave disturbances that travel across the tropical and subtropical Pacific may also play a role as they reflect off the ocean-basin boundaries. Even random weather “noise” may initiate events in the coupled system that start an El Niño or La Niña. Perhaps there are multiple ways that an ENSO event can be triggered. Even so, the system’s inclination toward an ENSO event can be predicted with increasing success.

Predicting ENSO and its effects

Even before we know when or how a particular El Niño or La Niña is going to evolve, we can say something about the regional and global effects it is likely to have. This is due to teleconnections: physical relationships that result from the dynamics of atmospheric and oceanic waves. The impact of teleconnections on weather patterns can be illustrated with statistics. Just as high pressure at Darwin tends to occur with low pressure at Tahiti, the presence of El Niño has been correlated with a number of wide-ranging atmospheric events. Figure 5 shows locations that have a consistent increase or decrease in precipitation during El Niño events, with

the most common months of that occurrence indicated. Some of the best-established effects are enhanced rainfall over the central Pacific, Peru, Ecuador, and the southern United States and drought in Australia, southern Africa, and northeastern Brazil.

In other locations, the impact of El Niño can have two or more different “flavors.” For instance, California can experience very wet conditions (such as in 1940–41, 1982–83, and 1991–92) or drought (1986–87 and 1987–88), depending on how far east the ENSO-related rainfall extends in the tropical Pacific. Predicting which flavor will dominate for a given event is difficult, because very small changes in SSTs

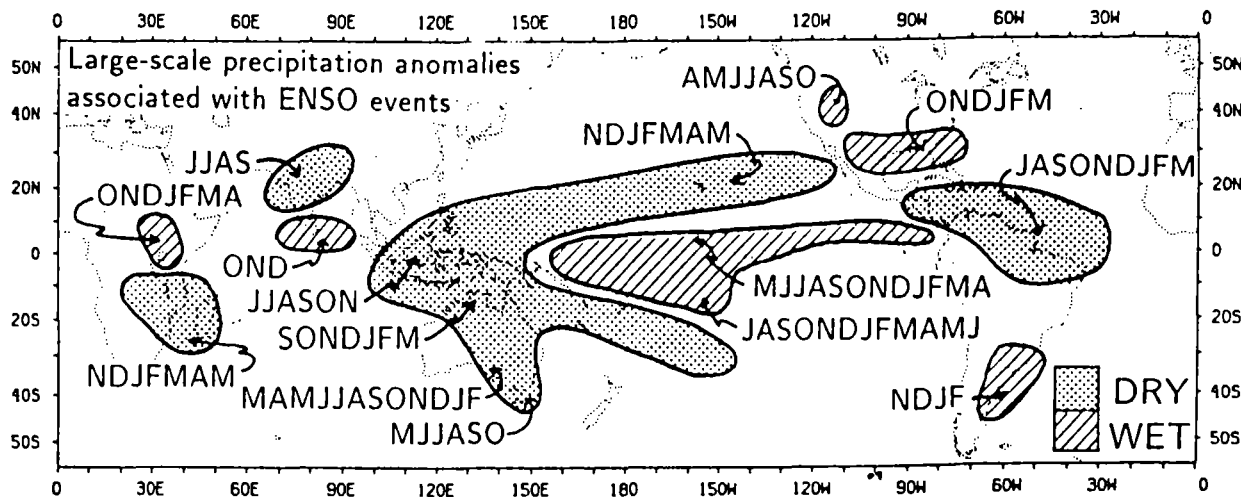


Figure 5: This schematic shows areas that have a consistent change in precipitation pattern linked to the first year of an El Niño event. The months in which the effect is seen are grouped by their first initials (e.g., OND is “October–November–December”).

A vast array of ships, aircraft, and buoys took weather readings throughout the western tropical Pacific as part of the Tropical Ocean and Global Atmosphere Program's Coupled Ocean-Atmosphere Response Experiment from November 1992 through February 1993. (Photo by Bob Bumpas.)



can become magnified to produce large differences in rainfall patterns outside the tropics. Precipitation in California is clearly connected to ENSO, but it may vary greatly from one El Niño to the next.

In another approach to prediction, some researchers are using computer models to attempt to reproduce the physics of the ocean and atmosphere as they evolve during ENSO events. This became possible in the 1980s as computer

power became sufficient to include ocean-atmosphere interactions in the large-scale climate models used to study such topics as greenhouse warming. Such models have been able to reproduce many of the oceanic and atmospheric effects of ENSO in the tropical Pacific, especially those that occur at the start of an El Niño event.

In 1990, a milestone was reached when the El Niño beginning late that year was successfully predicted months in advance by a

computer model at Lamont-Doherty Geological Observatory of Columbia University. Soon afterward, in 1992, NCAR produced the first model to show the evolution of ENSO-like behavior in an atmosphere containing twice the carbon

dioxide of the present (a state likely to be reached by the year 2050). The model indicates that the rainfall anomalies connected to El Niño and La Niña may become stronger in a global-warming scenario.

What are the remaining obstacles to predicting El Niño and La Niña? One is to better understand their cyclic yet variable beginnings and endings. The factors leading to the end of an El Niño event are not yet entirely clear, as evidenced by the recent failure of computer models to predict the end of the El Niño that began late in 1990. The Lamont-Doherty model called for the event to end in 1992. In late 1993, however, it was still in progress and actually intensifying, making it the longest-running El Niño in half a century.

To further complicate matters, the baseline against which El Niño and La Niña events are measured may itself be changing. Indications are that the average temperature of the tropical Pacific has risen slightly in the past decade or so. If so, a new benchmark for measuring the onset and conclusion of ENSO events may have to be set.

Improvements in tropical-ocean observation will help advance research on ENSO. Buoys that measure ocean temperature to a depth of up to 500 meters

(1,650 feet) are now moored throughout the tropical Pacific. A giant field program was mounted in the western Pacific in late 1992 and early 1993, the Tropical Ocean and Global Atmosphere Program's Coupled Ocean-Atmosphere Response Experiment. The wealth of data from that program, the Central Equatorial Pacific Experiment (held in spring 1993), and long-term moored instruments will help scientists better understand the tropical Pacific waters.

These lines of research point toward the day when ENSO events can be reliably predicted months ahead of time. Such information could be of great benefit in planning for drought, flood, and temperature extremes and in mitigating the associated pain and damage. If we cannot hope to control the effects of ENSO, there is real hope that we can understand and forecast its on-off switch.

Much of the information and graphics in this report was drawn from "General Characteristics of El Niño-Southern Oscillation," by Kevin Trenberth, in *Teleconnections Linking Worldwide Climate Anomalies*, edited by Michael Glantz, Richard Katz, and Neville Nicholls (Cambridge University Press, 1991).

Forecast frontiers

**ENSO:
SST MONTHLY MEAN ANOMALIES
PACIFIC SECTOR
JANUARY 1982 - JULY 1992**

Produced by
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NATIONAL CENTER FOR ATMOSPHERIC RESEARCH
P. O. Box 3000, Boulder, CO 80307**

December 1992

The accompanying video provides animated sequences of:

- the mean annual cycle of sea surface temperatures (SSTs)
- the SST anomalies from January 1982 to July 1992

in the Pacific Ocean where the dominant global SST variability is seen as part of ENSO: the El Niño-Southern Oscillation phenomenon.

Observed SSTs were provided by the Climate Analysis Center, NOAA.

The National Center for Atmospheric Research is sponsored by the National Science Foundation.

This video was partially sponsored by the Tropical Ocean Global Atmosphere Project Office under grant NA87AANRG0208.

ENSO: El Niño-Southern Oscillation

One of the most prominent sources of **INTERANNUAL VARIABILITY** in **WEATHER** and **CLIMATE** around the world. It constitutes the **MOST DRAMATIC AND ENERGETIC WELL-DEFINED PATTERN** of interannual variability.

EL Niño: The Ocean part of ENSO.

- **Warming of tropical Pacific**
Originally referred to a warm current off Peru that penetrated south about Christmas (hence Niño: Christ child)
- **Became associated with extreme excursions: anomalous events.**
Moreover it has since been discovered that El Niño events along the coast of South America are also associated with Pacific basin-scale SST warming and that it is this basin-scale phenomenon that is responsible for the global-scale climate anomalies. Because there is a close, but not one-to-one, association between the coastal and basin-scale events, the term "El Niño" has also been widely used for the basin-scale phenomenon, leading to considerable confusion in the terminology.

Southern Oscillation: The atmospheric part of ENSO.

- Global atmospheric wave pattern
- Main centers: Indonesia, South Pacific, tropics and subtropics
- Seasonal teleconnections to higher latitudes

ENSO: Warm Pacific events with EN and SO together.
Occur about every 4 years (2-7 years)

Recent ENSO events: 1982-83, 1986-87, 1991-92.

1982-83 This was the most extreme event over past century. It was accompanied by Widespread droughts and fires in Australia, S. Africa, West Pacific Islands, North-east Brazil, and southeast Asia. At the same time there was extensive flooding in Peru and Ecuador and the wettest winter and spring on record in the West and Southwest United States. High sea levels along the coast of the Americas (about 1 foot above normal) caused extensive coastal damage.

La Niña: Cold event in the tropical Pacific.

1988-89 Severe drought and extensive fires occurred in North America during the spring and summer of 1988, and droughts also occurred in Uruguay, Argentina, and east New Zealand. At the same time there were floods in east Asia, west New Zealand and Australia.

Damage directly attributable to these two extremes of the ENSO phenomenon reaches into tens of billions of \$US with both floods and droughts.

ENSO

A natural mode of the coupled ocean-atmosphere system

ENSO events have been going on for centuries (as recorded in corals, and in ice layers in glaciers in South America).

ENSO is a natural phenomenon.

ENSO arises from air-sea interactions in the Pacific.

1. The atmospheric trade winds drive the tropical ocean currents and determine the SSTs. Upwelling and advection are important.
2. The rainfall in thunderstorms and organized convection gives rise to latent heat release in the atmosphere, which determines atmospheric heating patterns.
3. The heating patterns set up waves in the atmosphere that propagate to other regions (teleconnections) and determine the atmospheric circulation locally.
4. Thus the jet stream in mid-latitudes is displaced from its normal position and this changes the storm tracks.

ENSO is a positive feedback loop where a change in the

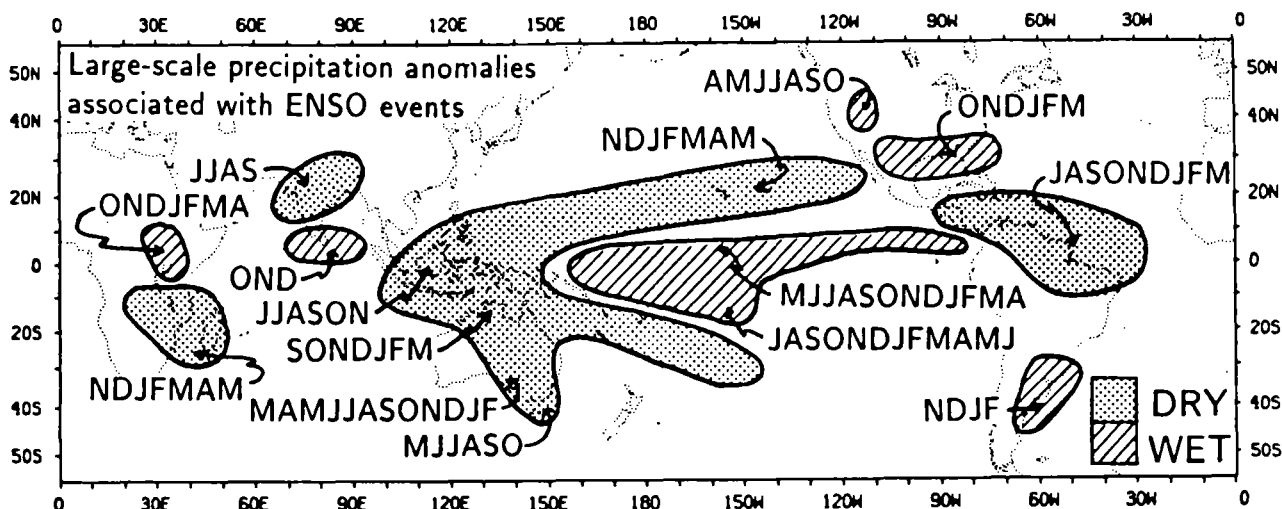
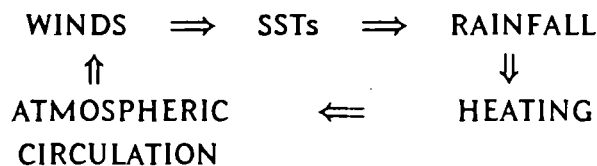


Fig. 1. Schematic areas influenced by ENSO in terms of precipitation. The months indicated are those affected during the year of and the year following the ENSO event (from Trenberth, 1991).

Correlations of Annual Mean Sea Level Pressure with Darwin

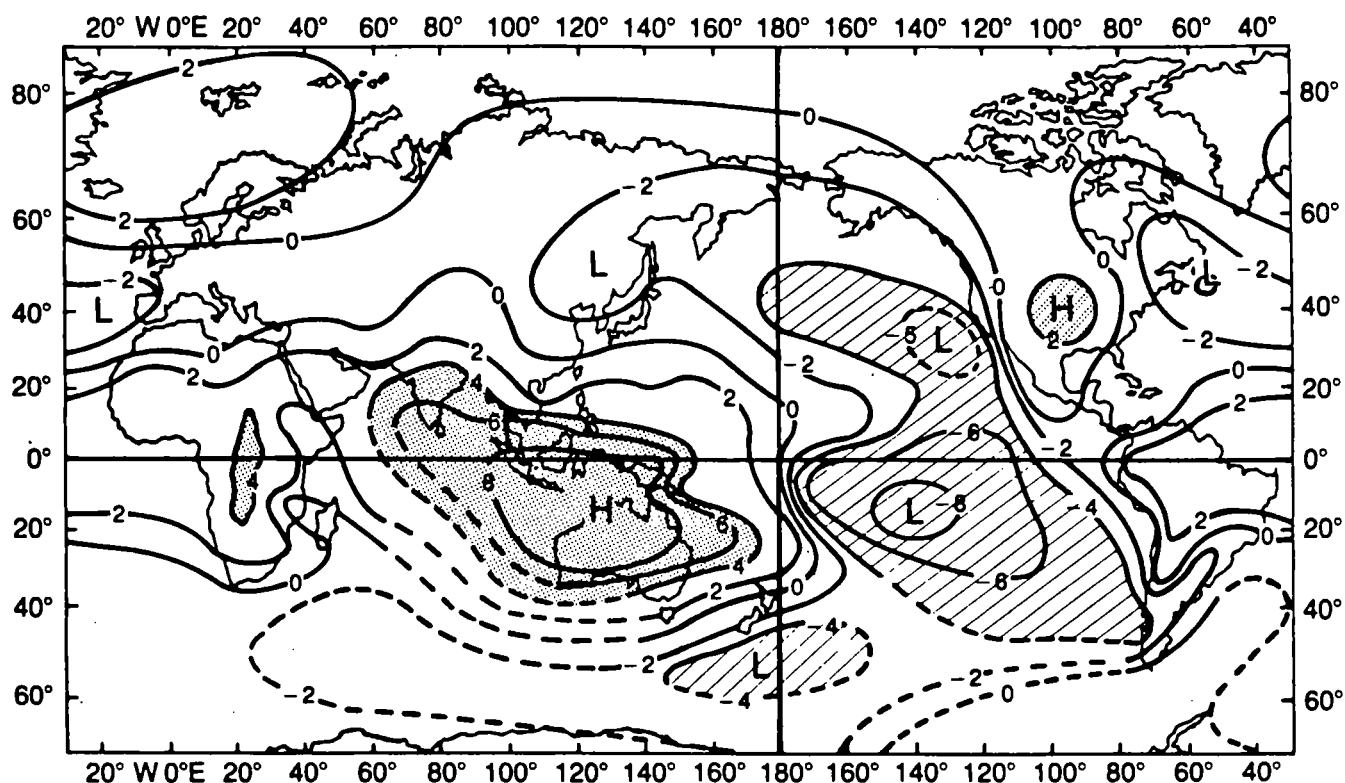


Fig. 2. Pressure patterns associated with the Southern Oscillation as given by correlations ($\times 10$) of annual mean sea level pressures with Darwin (from Trenberth and Shea, 1987).

Southern Oscillation Index

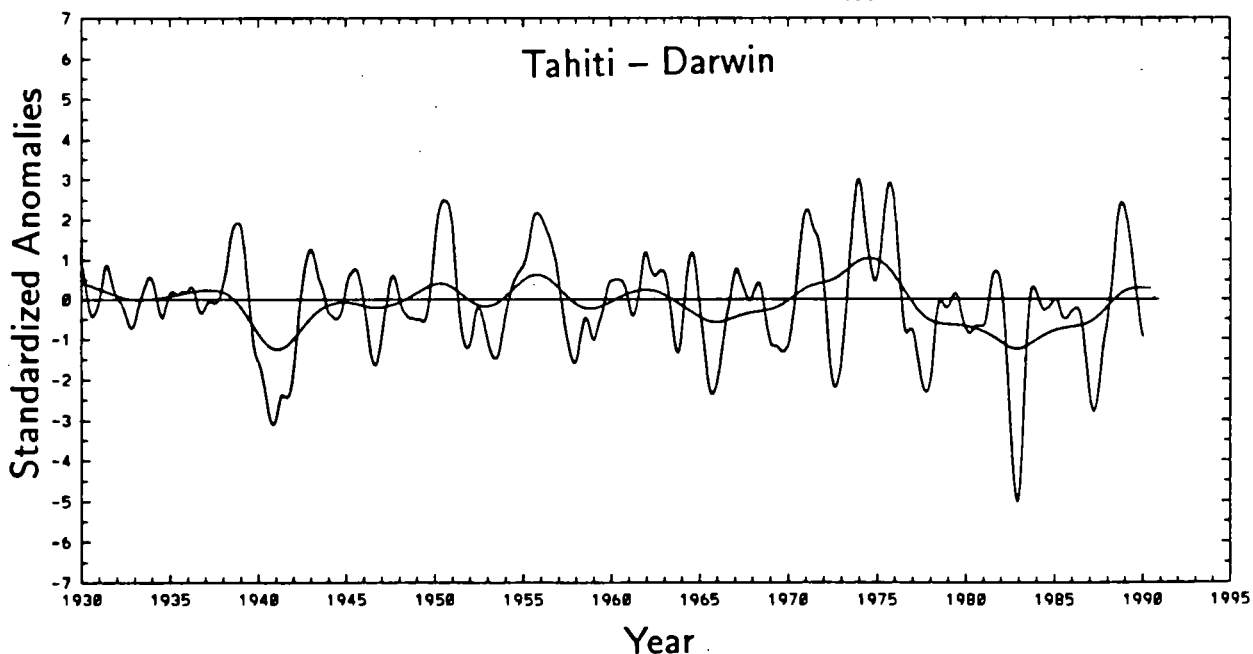


Fig. 3. Time series of the Southern Oscillation index from 1930 to 1990 as given by pressures at Darwin (northern Australia) and Tahiti (tropical South Pacific). Negative values indicate El Niño events and positive values La Niña events.

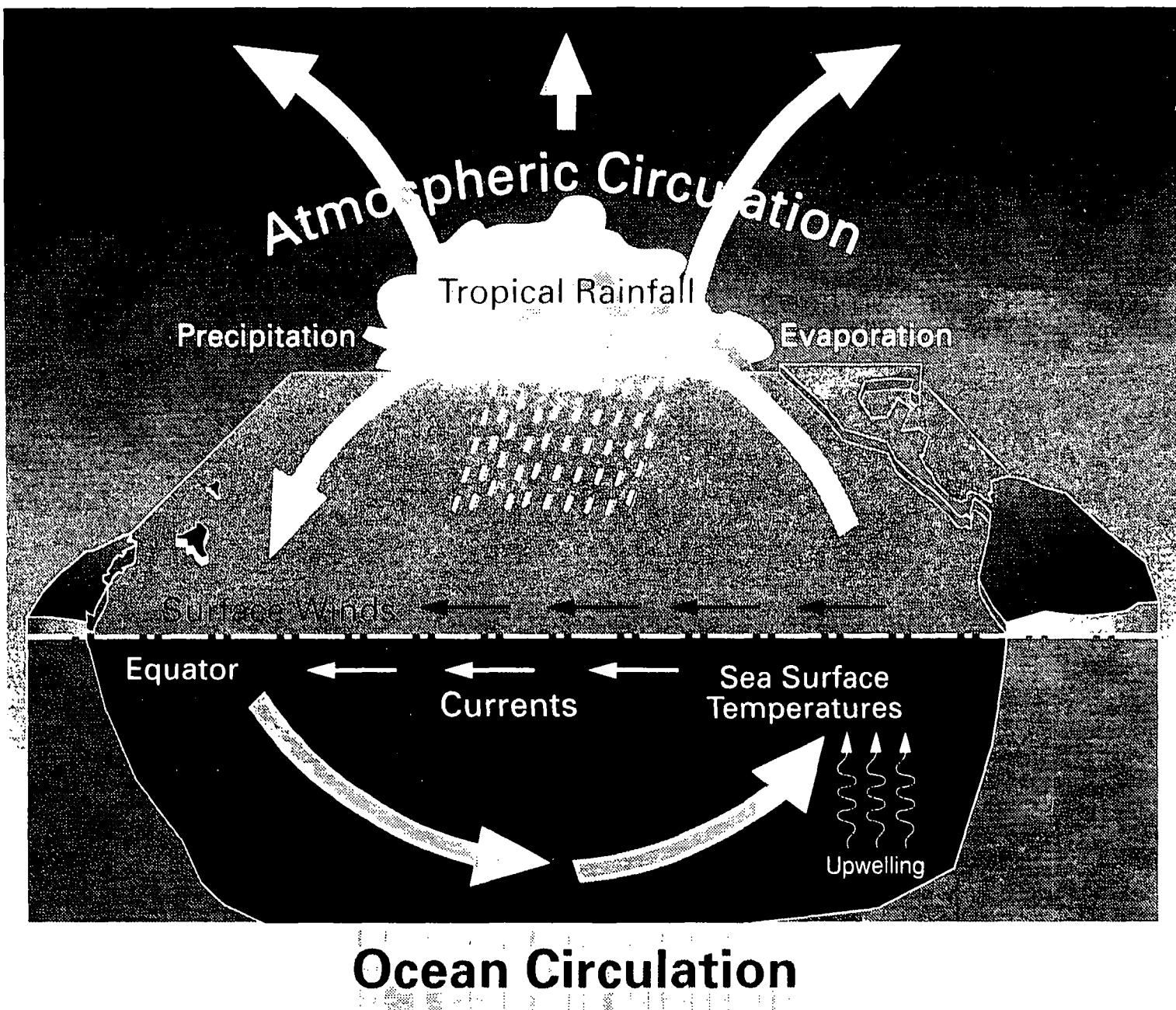


Fig. 4. Schematic of the important physical links between the atmosphere and ocean involved in ENSO.

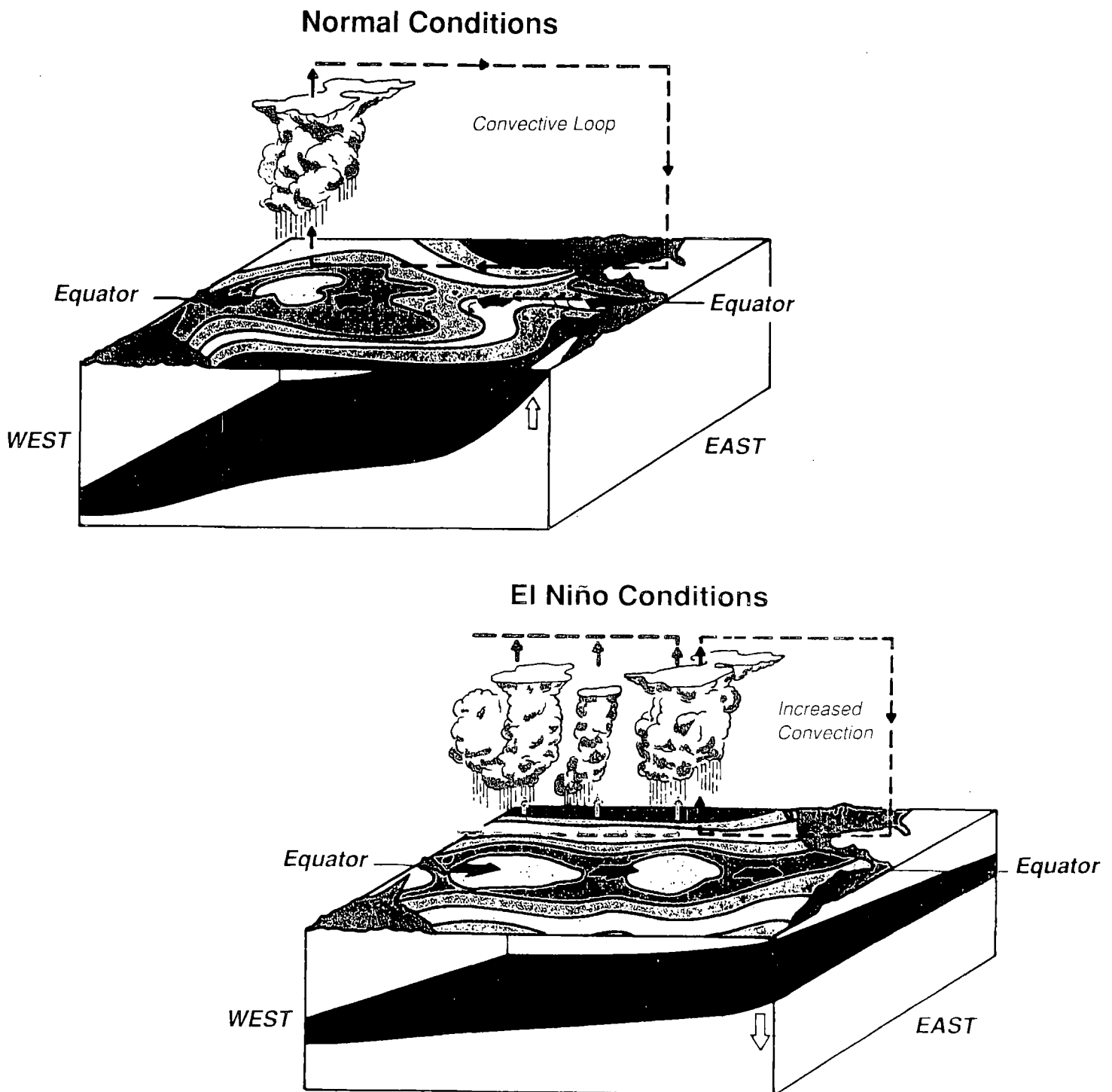


Fig. 5. Schematic cross sections of the Pacific under normal conditions (top) and El Niño conditions (bottom). Shown are the SST patterns (orange corresponds to SSTs greater than 29°C and with a 1°C contour interval), the thermocline (which divides the cold deep ocean from the mixed surface layers), and the change in tropical atmospheric convection in the form of organized thunderstorm activity. Steady tradewinds blowing east to west along the equator in the top panel induce upwelling of colder waters from below and surface divergence, as shown by the small arrows. Under El Niño conditions, upwelling may cease, especially in the central and western Pacific or, if it continues in the eastern equatorial Pacific, warmer water is upwelled because of the displaced thermocline.

SST ANOMALIES - DECEMBER 1982

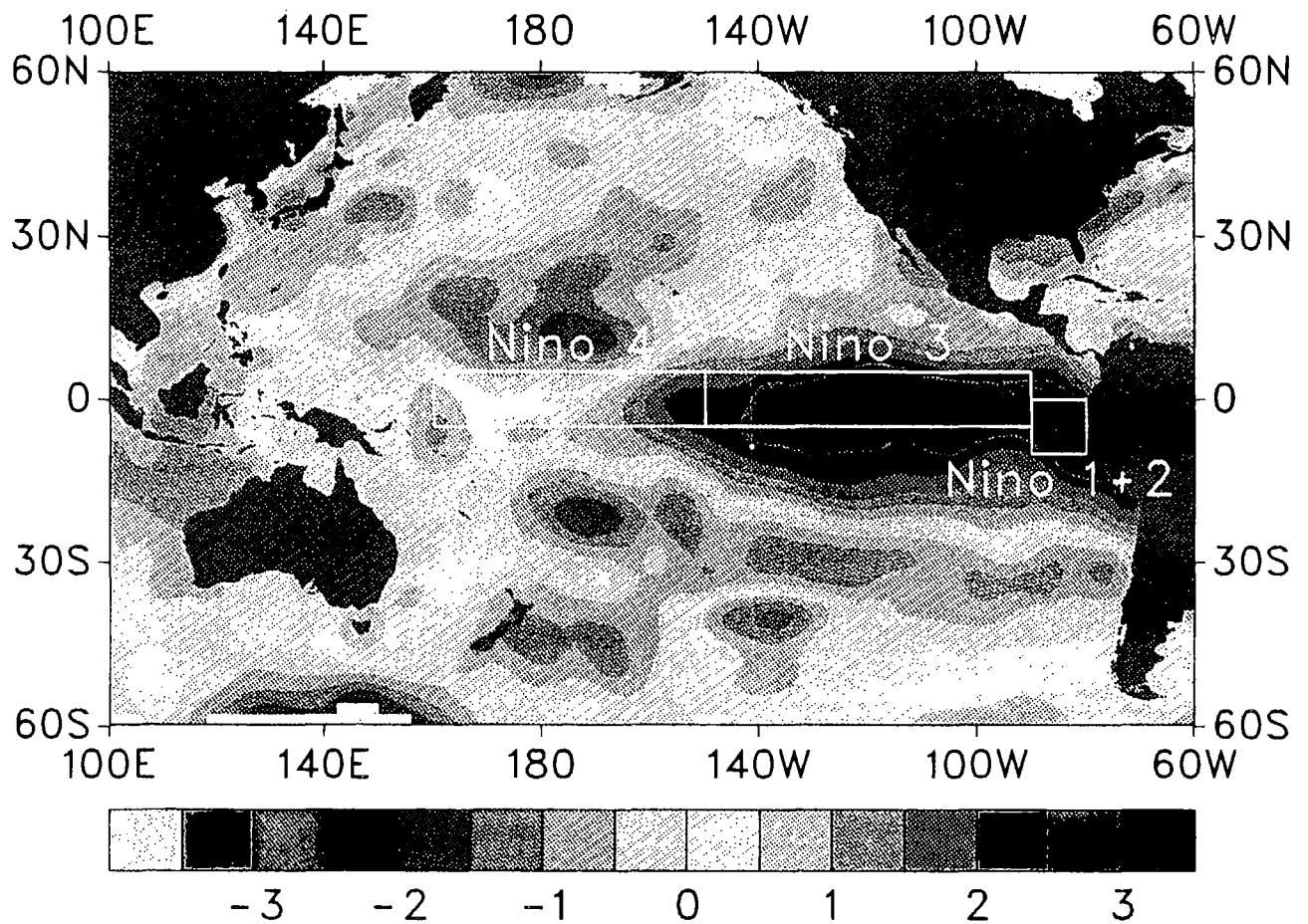


Fig. 6. A sample plot from the video for December 1982, at the height of the 1982-83 ENSO event. Superimposed are boxes in yellow showing the Niño regions over which area averages of SST anomalies are computed as indices of the overall state of the SSTs in the tropical Pacific.

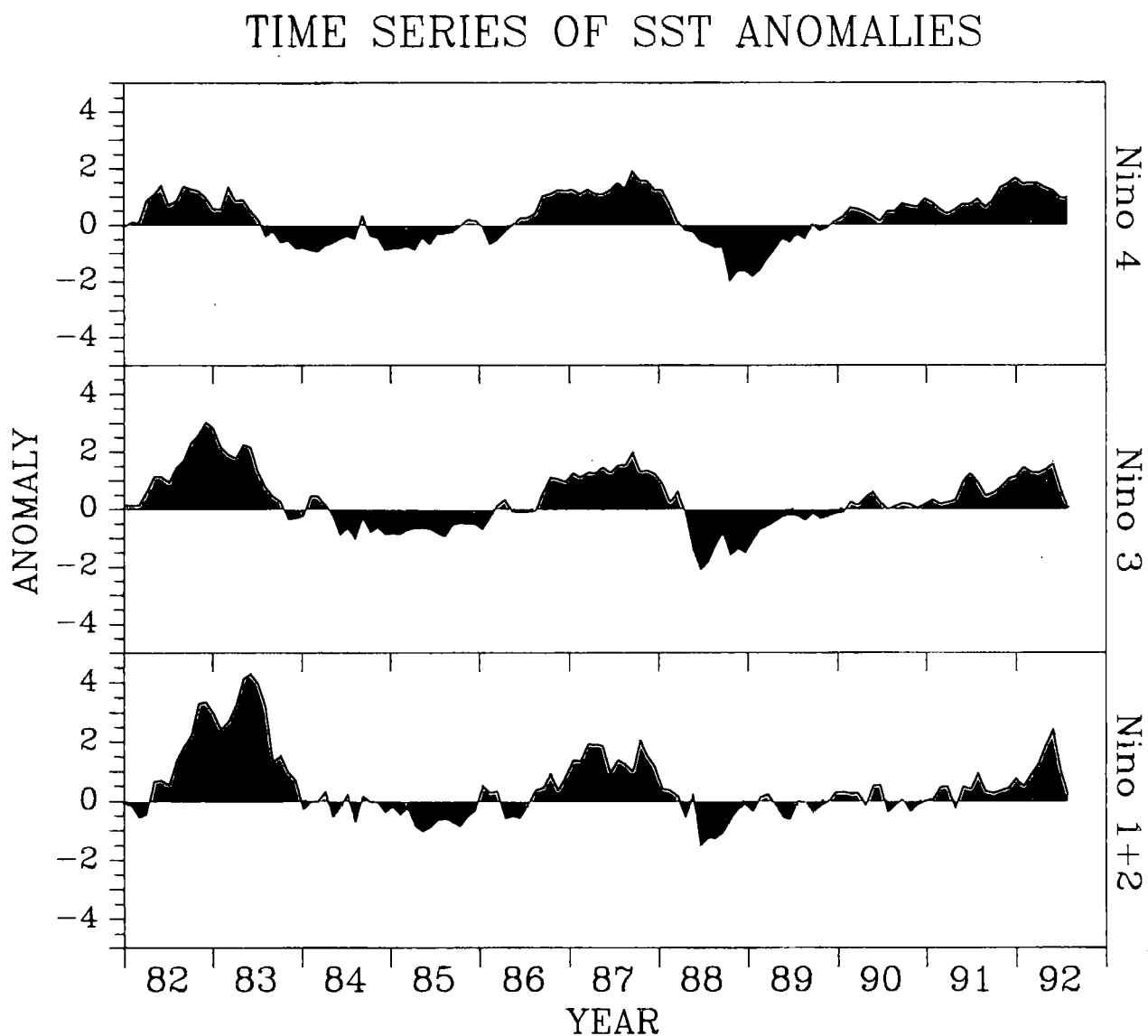


Fig. 7. Time series of SSTs in the Niño regions defined in Fig. 6 for the period covered by the video. Positive anomalies in red indicate El Niño events and negative anomalies are indicated in blue. Only the 1988-89 period is designated as a La Niña.

How may ENSO events change with GLOBAL WARMING?

Climate models now suggest that both extremes of ENSO may be extended so that both floods and droughts may get worse, even if average rainfall changes little. This is because of enhanced evapotranspiration in droughts with increased greenhouse gases and an enhanced hydrological cycle overall.

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DECADAL VARIABILITY AND CLIMATE CHANGE IN LARGE-SCALE INTERACTION BETWEEN THE ATMOSPHERE AND THE OCEAN

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Contribution to IPCC 1995 assessment, Chapter 7

1. INTRODUCTION

The winter of December 1993–February 1994 was very cold and snowy with many more than normal winter storms in the northeastern part of the United States. Many questions were raised by the media on how this jibes with expectations of global warming. The exceptionally wintry weather continued for several months, long enough to create a pattern of behavior. However, as part of this pattern there were often mild and sunny conditions in the western half of the United States and Canada, and temperatures there were somewhat above average. Examination of the hemispheric maps for the winter reveal temperatures of 4°C below normal in the vicinity of the Great Lakes with the anomalies below the ten percentile throughout the eastern part of Canada from Hudson Bay to the Great Lakes and including parts of the United States in the northeast. But temperatures were above normal over much of the rest of the hemisphere and exceeded the ninetieth percentile in parts of Southeast Asia, northern Africa and the Mediterranean, and the West Indies, so the global implications are much less clear.

Moreover, the pattern of change that has been occurring since the late 1970s has been one favoring warming in the western part of North America but little warming, or even slight cooling, in the eastern part. This distinctive pattern of change involves the ocean, for instance as seen through sea surface temperatures, and it has occurred throughout the Pacific and is linked to changes in the tropics. While not predicted by models, this observed teleconnection pattern is a part of an ongoing climate change and it complicates the interpretation of the role of the greenhouse gas forcing.

One issue is the fact that global warming does not mean that it should warm everywhere at once, as is sometimes inferred. It does suggest that the global average should increase but that regionally there can be marked discrepancies. The observed presence of strong regional patterns of change must be recognized in interpreting the climate record and in tempering expectations. Is this pattern of change one that is a part of global warming but one which is not well handled by the models? Or is this pattern a natural decadal-timescale variation so that any global warming signal has to be distinguished from natural variability?

Analysis of decadal variability is difficult because of the relatively short high quality observational records available.

In the past few years, however, considerable work has been done to bring out the decadal and longer time-scale variability regionally in several parts of the globe. In particular, there has been one focus on the North Pacific (Trenberth, 1990; Trenberth and Hurrell, 1994a, 1994b; Nitta and Yamada, 1989; Wallace et al. 1993; Chen et al., 1992; Graham, 1994; Deser and Blackmon, 1994; Zhang et al., 1994) which is also linked strongly to the tropical Pacific and Indian Ocean variations. A second focus has been on the North Atlantic where decadal period fluctuations have been found superposed on a longer period (about 70 year) variation (Deser and Blackmon, 1993; Kushnir, 1994; Hurrell and van Loon, 1993; Schlesinger and Ramankutty, 1994) which may be related to the apparently rapid changes found in inferred temperatures from ice cores in the Greenland icecap. A third focus has been on the Southern Hemisphere, especially in the Pacific (van Loon et al., 1993, Hurrell and van Loon, 1994). We briefly discuss these in turn.

2. THE NORTH PACIFIC

Decadal variability in the Pacific exists strongly in winter with the period of the fluctuations exceeding 20 years (Trenberth and Hurrell, 1994a). Considerable evidence has emerged of a substantial at least decade-long change in the North Pacific atmosphere and ocean beginning about 1976 and lasting until at least 1988. Whether this is continuing can not be determined without a longer perspective. Observed significant changes in the atmospheric circulation involve the so-called Pacific-North American (PNA) teleconnection pattern, so that for this period, throughout the troposphere there was a deeper and eastward shifted Aleutian low pressure system in the winter half year which advected warmer and moister air along the west coast of North America and into Alaska and colder air over the North Pacific (Trenberth, 1990; Nitta and Yamada, 1989; Trenberth and Hurrell, 1994a). Consequently, there were increases in temperatures and sea surface temperatures (SSTs) along the west coast of North America and Alaska but decreases in SSTs over the central North Pacific (Tanimoto et al., 1993; Trenberth and Hurrell, 1994a; Kawamura, 1994), as well as changes in coastal rainfall and streamflow (Cayan and Peterson, 1989) and decreases in sea ice in the Bering Sea (Manak and Mysak, 1987).

¹ The National Center for Atmospheric Research is sponsored by the National Science Foundation.

Associated changes occurred in the surface wind stress, and, by inference, in the Sverdrup transport in the North Pacific Ocean (Sekine, 1988; Trenberth, 1991) that have been directly measured in the Gulf of Alaska (Royer, 1989). Bakun (1990) has noted changes in the longshore windstress off California that are probably related. There is also emerging evidence for increased tropospheric temperatures and water vapor in the western tropical Pacific after 1976 (Hense et al., 1988; Gaffen et al., 1991).

Changes in the mean flow were accompanied by a southward shift in the storm tracks and associated synoptic eddy activity (Trenberth and Hurrell, 1994a) and in the surface ocean sensible and latent heat fluxes (Cayan, 1992). Also accompanying the changes in the Pacific were higher incidences of cold outbreaks across the plains of North America ultimately leading to major freezes affecting the Florida citrus crop (Rogers and Rohli, 1991; Downton and Miller, 1993).

In addition to the changes in the physical environment, the deeper Aleutian low increased the nutrient supply as seen through increases in total chlorophyll in the water column, phytoplankton and zooplankton (Venrick et al., 1987). These changes, along with the altered ocean currents and temperatures, changed the migration patterns and increased the stock of many fish species (Mysak, 1986; Hamilton, 1987; McFarlane and Beamish, 1992; Beamish and Bouillon, 1993; Brodeur and Ware, 1993; Trenberth and Hurrell, 1994b; Polovina et al., 1994).

The dominant atmosphere-ocean relation in the North Pacific is one where atmospheric changes lead SSTs by one to two months, apparently because of the changes in surface sensible and latent heat fluxes combined with mixing in the ocean and entrainment. Changes in the storm tracks in the North Pacific help to reinforce and maintain the anomalous circulation in the upper troposphere. Trenberth and Hurrell (1994a) have also shown that strong ties exist between the North Pacific changes and events in the tropical Pacific, with changes in tropical Pacific SSTs leading SSTs in the North Pacific by three months. The Pacific decadal timescale variations have been linked to recent changes in the frequency and intensity of El Niño versus La Niña events and it has been hypothesized that the decadal variation has its origin in the tropics (Trenberth and Hurrell, 1994a). Further analyses of observations (Deser and Blackmon, 1994; Zhang et al., 1994) have not been able to confirm this link although several aspects of the decadal-scale change beginning around 1976 have been simulated with atmospheric models using specified SSTs (Kitoh, 1991; Chen et al., 1992; Graham, 1994; Miller et al., 1994; Kawamura et al., 1994). These studies do confirm that the atmospheric changes are tied to the changes in SSTs, and that the changes over the North Pacific are substantially controlled by the anomalous SST forcing from the tropics. Yamagata and Masumoto (1992) have suggested, however, that the decadal time-scale variations may also involve the Asian monsoon system.

The changes in lower tropospheric temperatures in the North Pacific winter do not have much influence on the hemispheric or global mean because there is strong cancel-

lation by regional anomalies of opposite sign (Wallace et al., 1993), and instead the global mean is associated with a different mode which is present in all seasons and which is also present in the Atlantic sector. However, lower tropospheric temperatures, such as given by the 1000-500 mb thickness, differ somewhat from surface temperatures (Trenberth et al., 1992) because of the land-ocean differences in the underlying surface in regions of surface temperature anomalies of opposite sign. Differences in heat capacity amplify temperature anomalies over land.

3. THE NORTH ATLANTIC

In the North Atlantic, decadal period fluctuations have been found superposed on a longer period (about 70 year) variation (Deser and Blackmon, 1993; Kushnir, 1994; Hurrell and van Loon, 1993; Schlesinger and Ramankutty, 1994) which is reflected in the global mean temperature variations. Earlier studies of the North Atlantic are reviewed by Trenberth (1993).

In the Atlantic, one mode of decadal variability is shorter in timescale than that in the Pacific and the mode is also found to vary on quasibiennial timescales. The irregular fluctuations average about 9 years in length before about 1945 and about 12 years thereafter. The mode is characterized by a dipole pattern in SSTs and surface air temperatures, with anomalies of one sign east of Newfoundland, and anomalies of opposite polarity off the southeast coast of the United States in the Atlantic. Distinctive sea level pressure and wind patterns have been identified with this mode and seem to be of the nature that the SSTs result largely from the winds, with cooler-than-normal SSTs accompanied by stronger-than-normal winds (Cayan, 1992; Deser and Blackmon, 1993; Kushnir, 1994). The SST changes are closely associated with variations in sea ice in the Labrador Sea, with heavy sea ice preceding winters of colder than normal SSTs east of Newfoundland by about two years. The mode is identified with an atmospheric teleconnection pattern known as the North Atlantic Oscillation (Hurrell and van Loon, 1993) and the "West Atlantic" pattern at 500 mb (Deser and Blackmon, 1993).

The lower frequency mode is identified as a temperature fluctuation with period of about 65-70 years in the global mean temperatures but with largest amplitude in the North Atlantic and surrounding continents (Schlesinger and Ramankutty, 1994) where the period appears to vary somewhat regionally from 50 to 88 years. Relative to the record from 1850 on, it corresponds to a much colder period from the late 1800s to about 1920, much warmer than normal from about 1930 to 1960, and another cooler period in the 1970s and 1980s (Kushnir, 1994; Schlesinger and Ramankutty, 1994). The sea level pressures and surface winds associated with this pattern have been explored by Deser and Blackmon (1993) and Kushnir (1994) who find an anomalous cyclonic circulation during the warmer years and anticyclonic during the cooler years.

The nature of the relationships among the atmosphere and ocean variables is not fully understood although it seems

likely that it signifies the patterns of dynamical coupling between the atmosphere and ocean, which may extend outside the Atlantic domain. Because the surface changes are also reflected at depth in the ocean (Levitus, 1989) and changes in the Gulf Stream (Deser and Blackmon, 1993), the ocean circulation is clearly involved. Thus it is likely that there are changes in the ocean thermohaline circulation (Deser and Blackmon, 1993; Kushnir, 1994; Schlesinger and Ramanakutty, 1994) such as those seen in models with time scales of roughly 50 years (Manabe and Stouffer, 1988; Delworth et al., 1993) in which an intensified circulation is associated with surface warming at high latitudes of the North Atlantic and a poleward-shifted and intensified Gulf Stream. The thermohaline circulation is greatly influenced by density fluctuations at high latitudes which apparently arises mainly in the fresh water availability which alters salinity, and originates from changes in precipitation, runoff, and evaporation. These kinds of fluctuations may also be related to the abrupt climate changes seen in recent Greenland ice-core analysis (Taylor et al., 1993; Dansgaard et al., 1993).

4. THE SOUTHERN HEMISPHERE

Over the Southern Hemisphere, analysis of decadal variability is more difficult to assess because of the paucity of data. Nevertheless careful analysis of station data together with the available analyses have revealed decadal-scale climate changes that are not an artifact arising from changes in data or analyses (van Loon et al., 1993, Hurrell and van Loon, 1994). A change in the atmospheric circulation is most evident in the late 1970s with sea level pressures in the circumpolar trough generally lower in the 1980s than in the 1970s and with the changes most pronounced in the second half of the year, so that the tropospheric polar vortex remained strong into November and was associated with a delayed breakdown in the stratospheric polar vortex and the beginning of the ozone deficit in the Antarctic spring. (Hurrell and van Loon, 1994).

It is not believed that the ozone depletion was responsible for the change but it does highlight a dynamical component to the ozone hole problem. Instead it seems likely that the changes are associated with the increase in tropical sea surface temperatures and associated changes noted earlier for the North Pacific.

5. DISCUSSION

Because the atmosphere has a very short memory while the ocean has enormous thermal inertia it is widely assumed that it is the ocean that provides the important memory for decadal and longer-term climate variations. In fact, however, it is the collaborative interaction between the atmosphere and the ocean and other parts of the climate system that gives rise to the important climate variations. It is argued that constructive feedbacks between climate system components must be preferred over destructive interference modes (Trenberth and Hurrell, 1994a). As the observed variations reveal the very large scales that are apparently set by the scales of the atmospheric planetary-scale waves, the coupled

nature of the variations is emphasized.

Analysis of the changes in surface temperatures, winds and the various measures of the atmospheric circulation has shown coherent coupled variations on decadal and longer times scales that are especially important regionally. The regionalization appears to be more evident in the winter half year and is probably associated with the stronger dynamics operating then, while thermodynamic forcing can emerge more strongly in the summertime (Wallace et al., 1993). As a result, teleconnections are present in the winter extratropics and the changes seen at one location can be caused by local changes in quite remote regions, and especially from the tropics and subtropics.

The system appears to be one where considerable chaotic noise arising from weather systems is a prominent factor in the extratropics but where the patterns, as seen in decadal climate variations, are moulded by the tropical influences with the ocean selectively bringing out the long time scales. The ocean is never in equilibrium. Preferred SST anomaly patterns emerge because they help reinforce the atmospheric circulation patterns rather than destroying them, as is commonly the case. The spatial scales of the anomaly patterns, however, are set by the atmosphere.

Of particular note throughout the Pacific has been the changes that occurred in the late 1970s, and it is difficult to assess whether these are merely a part of natural variability or whether they are a complex response to anthropogenic-induced changes such as the increases in greenhouse gases. Palmer (1993) has emphasized that nonlinear dynamics may well change the frequency distribution of weather regimes in the atmosphere, rather than changing the regimes, so that counter-intuitive changes can occur. One example may be the changes throughout the Pacific involving the PNA teleconnection pattern in the Northern Hemisphere, which has resulted in a particular surface temperature pattern change that may have amplified the global surface temperature changes because of its interaction with land and ocean; temperature changes tend to be amplified over land and more subdued over the ocean because of the large heat capacity of the mixed layer of the latter.

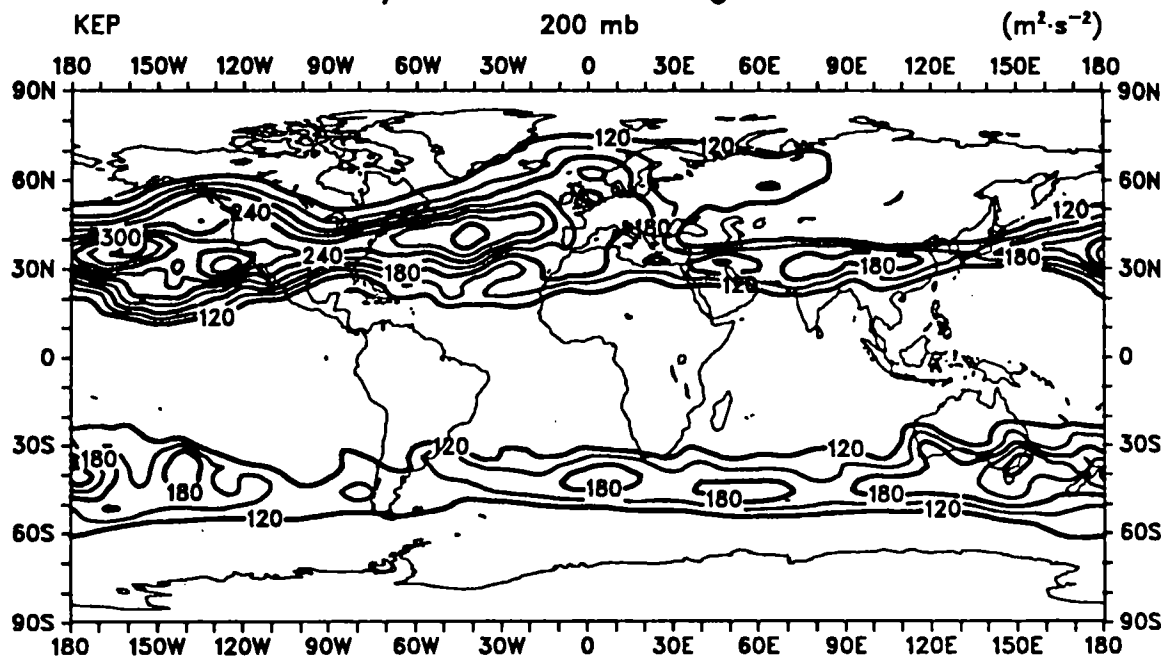
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Transient eddy kinetic energy $\rightarrow$ storm tracks

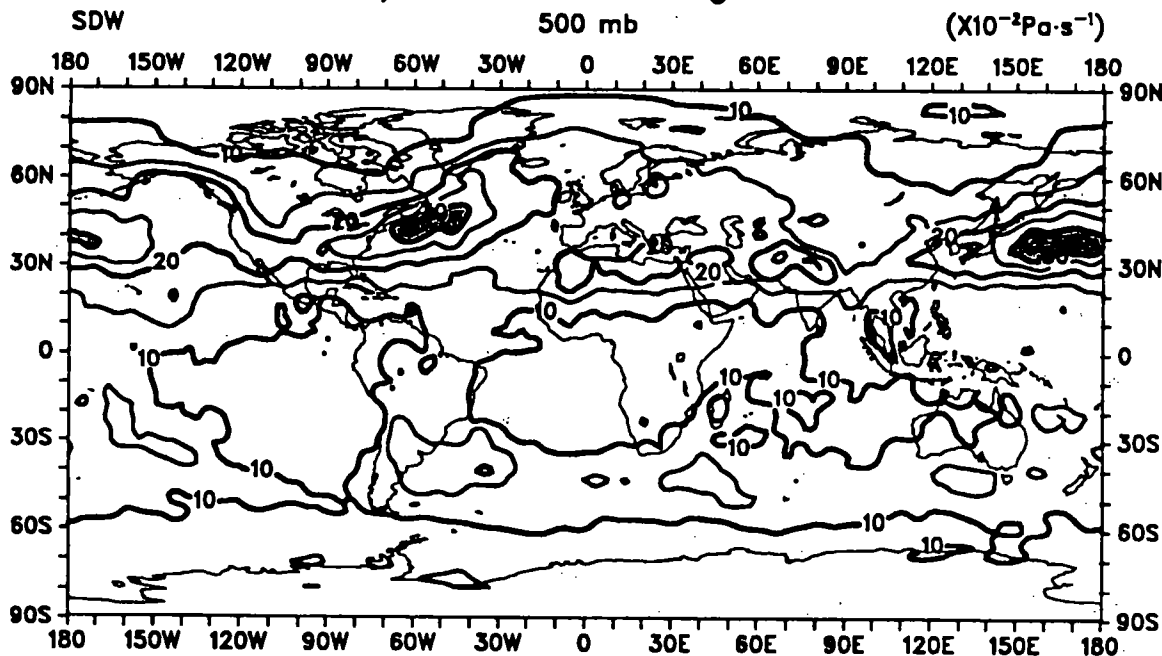
January Ensemble Average 1987-89



CONTOUR FROM 120 TO 360 BY CONTOUR INTERVAL 30

standard deviation of daily vertical motions in mid troposphere ~ 5 km

January Ensemble Average 1987-89 $\Rightarrow$ storm tracks



CONTOUR FROM 5 TO 30 BY CONTOUR INTERVAL 5

Fig. A27. $\frac{1}{2}(\overline{u'^2} + \overline{v'^2})$ at 200 mb and $s(\omega)$ at 500 mb for January.

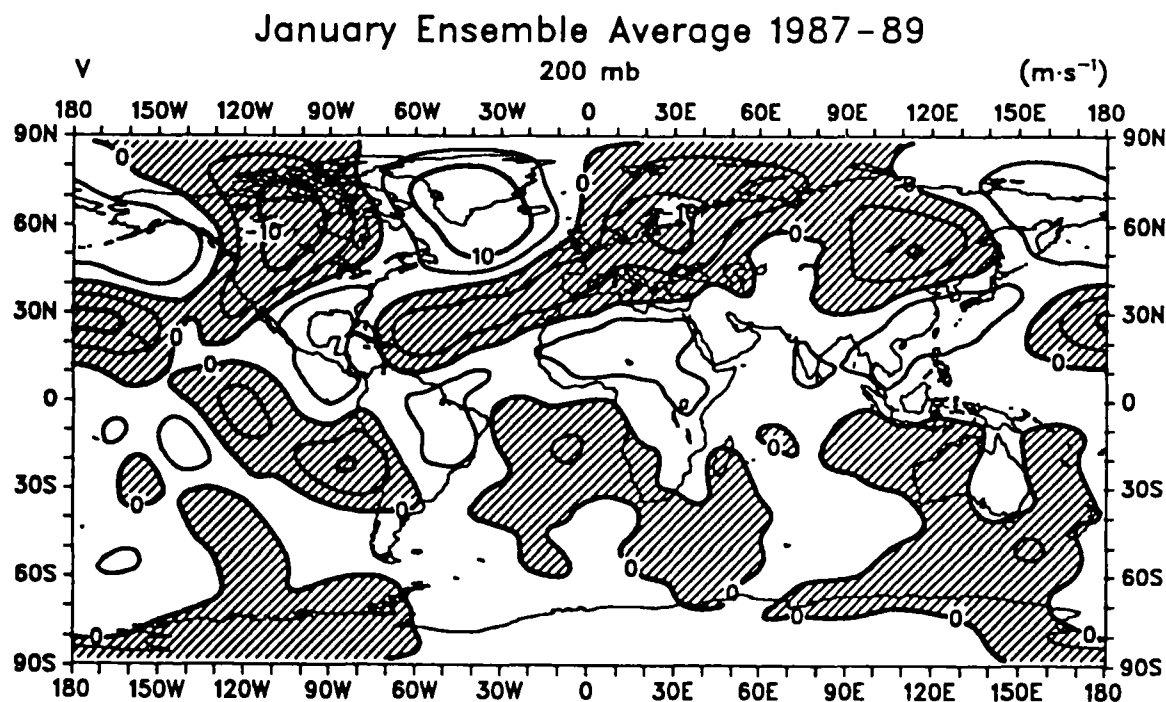
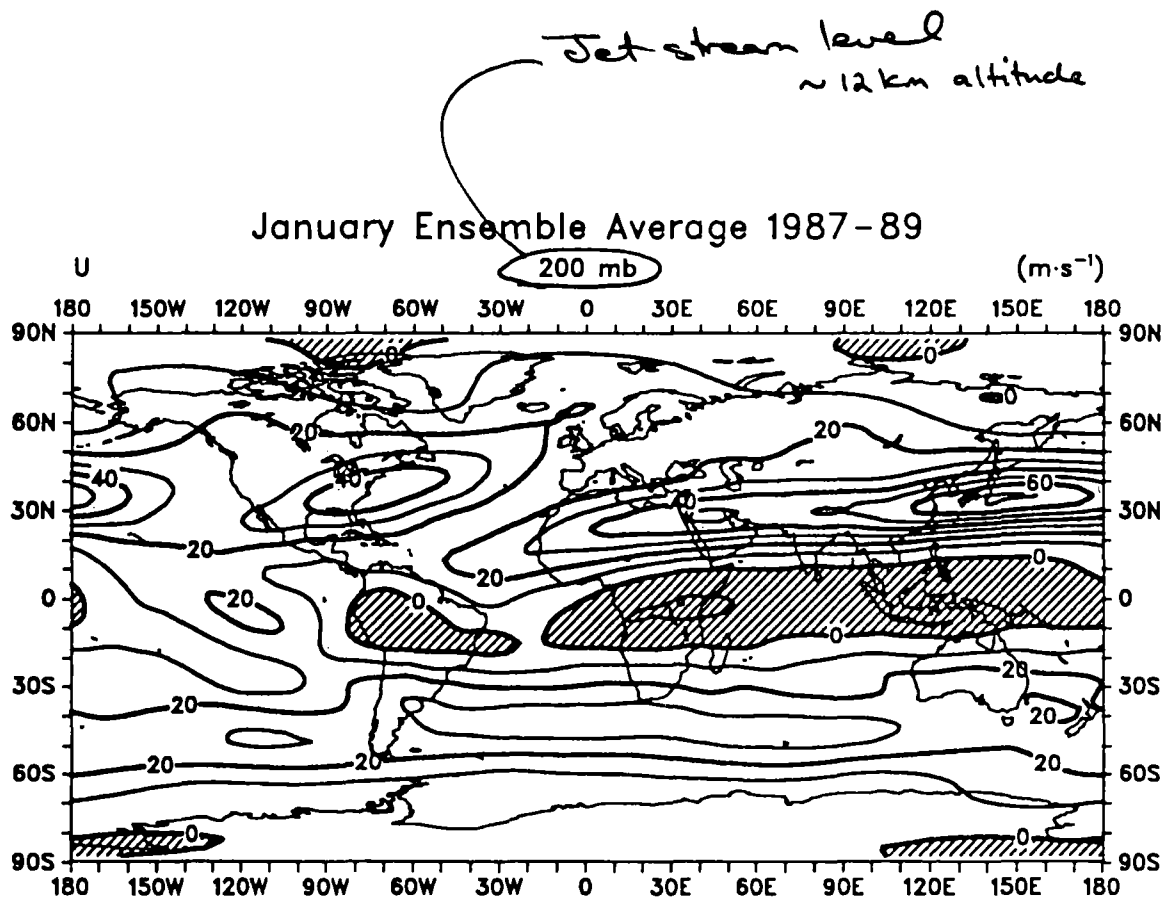
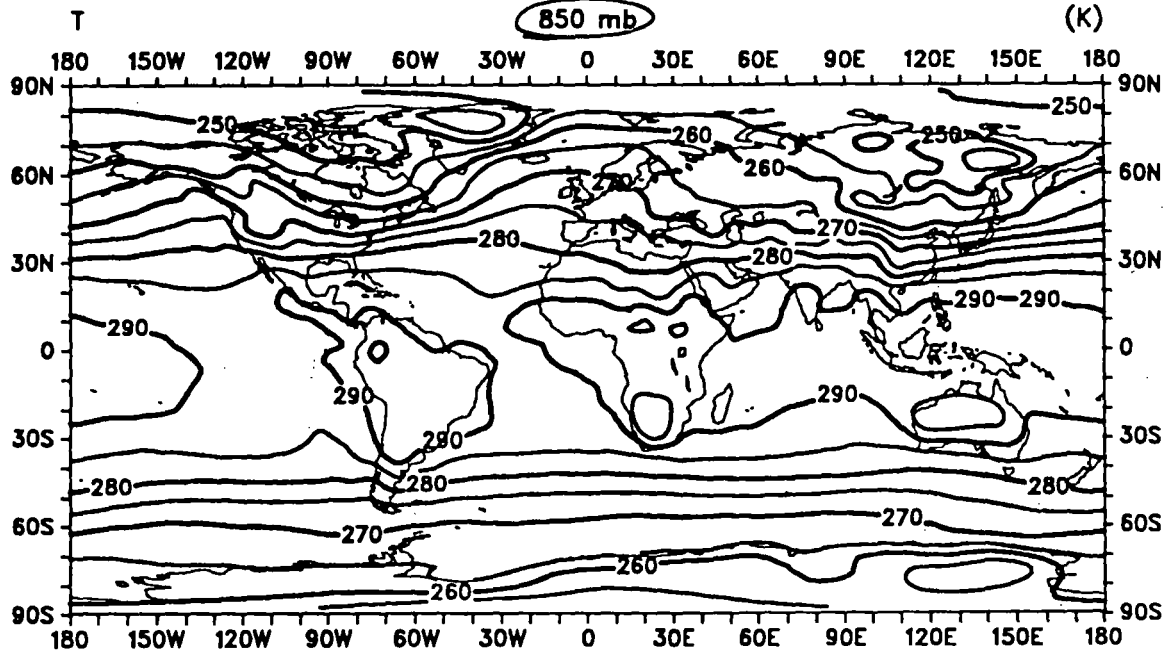


Fig. A13. $\bar{u}$ and $\bar{v}$ at 200 mb for January.

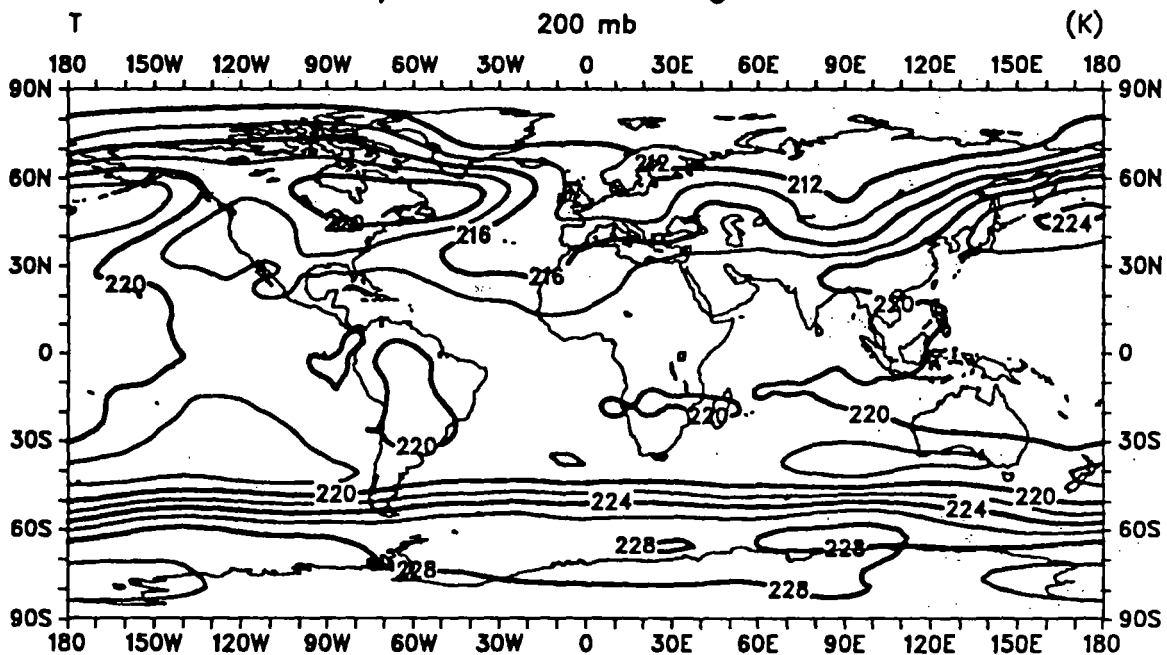
low troposphere
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January Ensemble Average 1987-89



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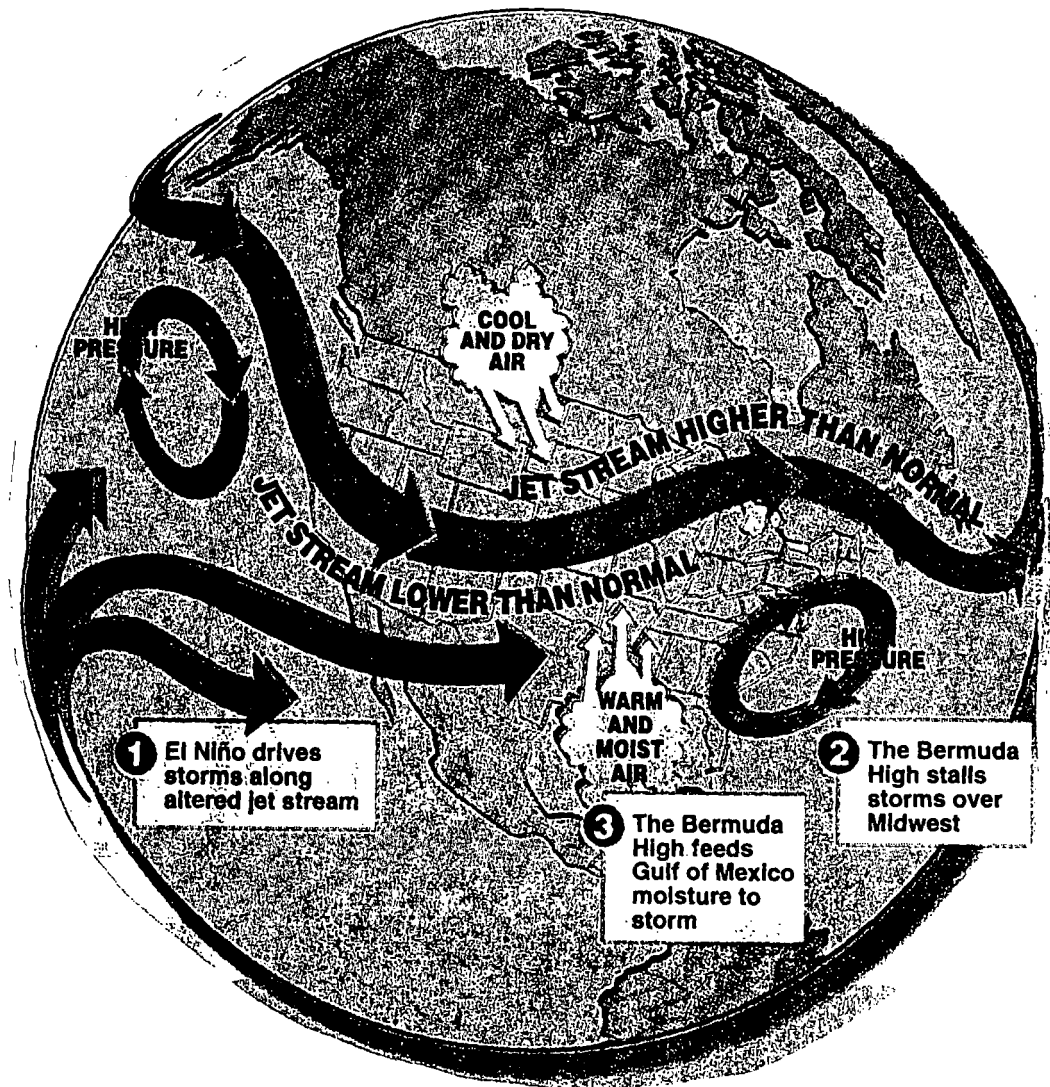
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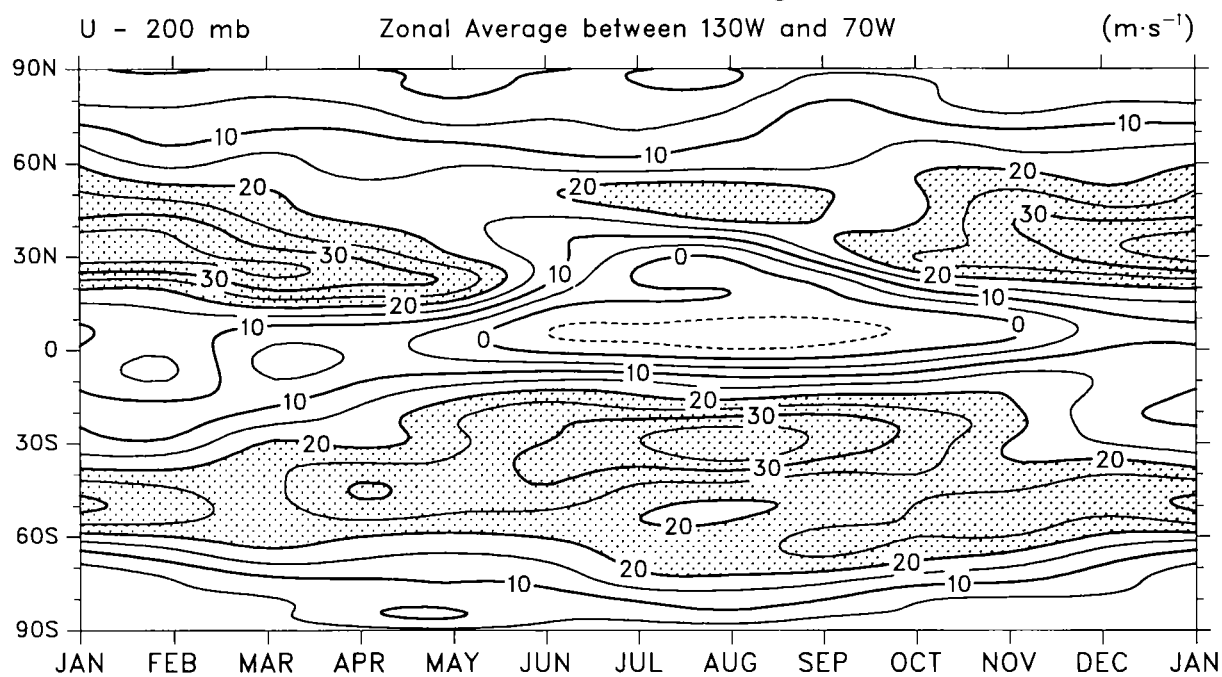
Fig. A19. $\bar{T}$ at 850 and 200 mb for January.

Star Tribune Aug 2 1993
Minneapolis, MN



K.Trenberth NCAR

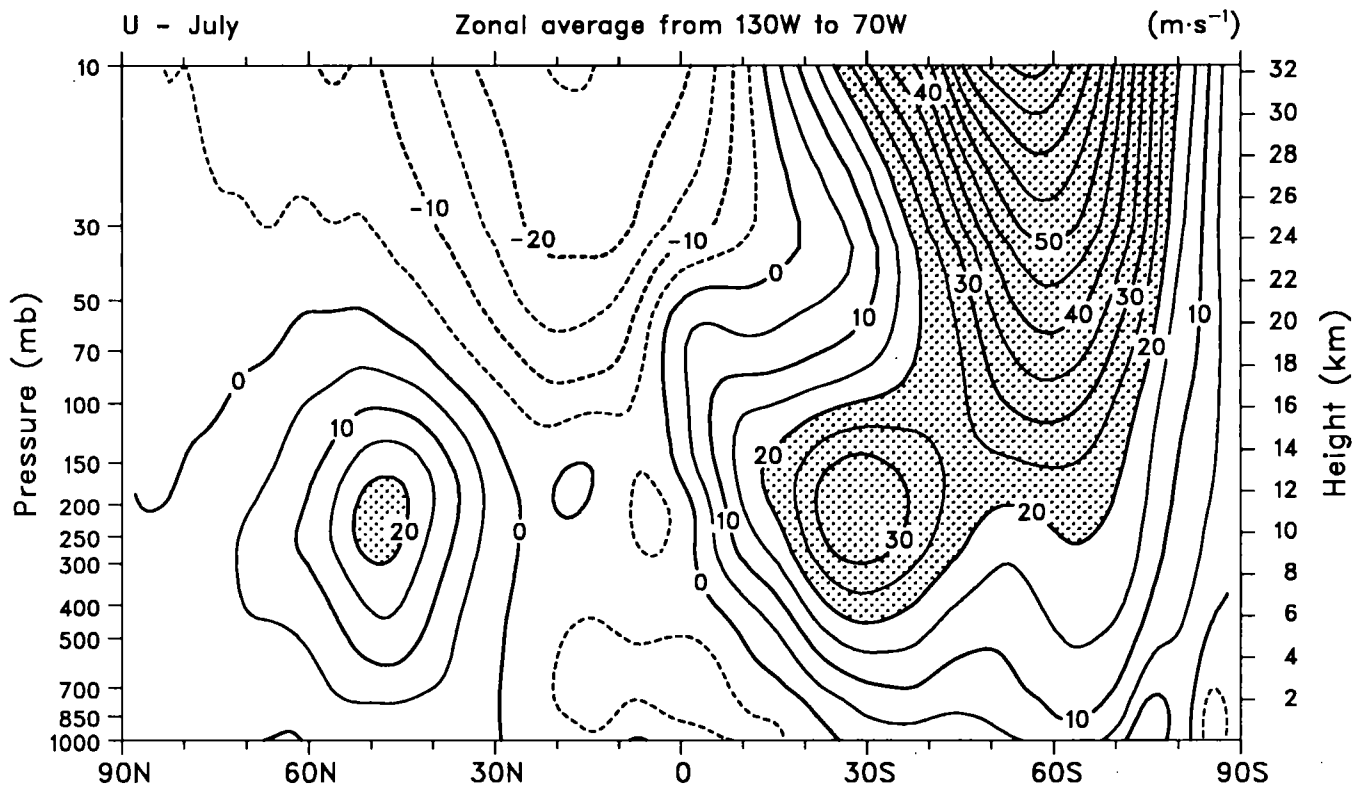
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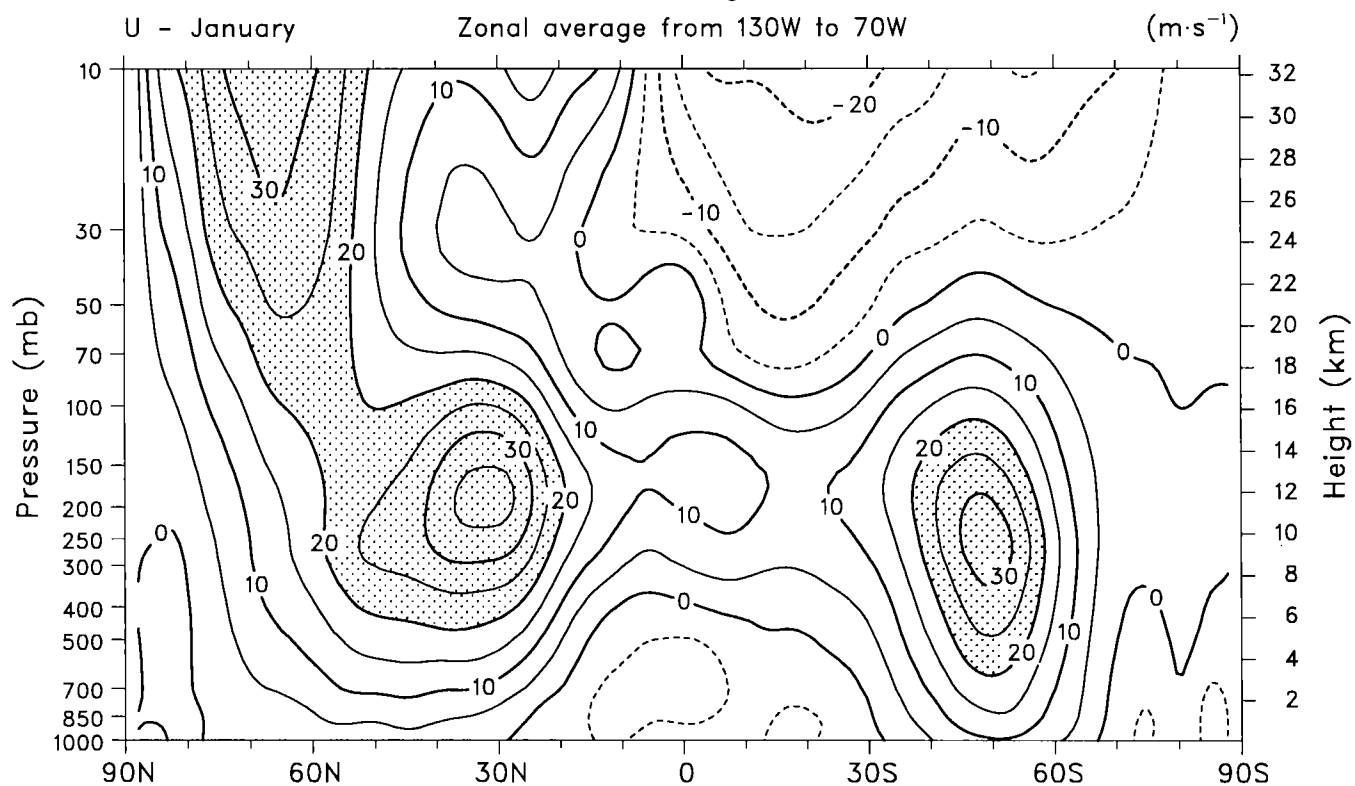
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Ensemble Average 1987-89



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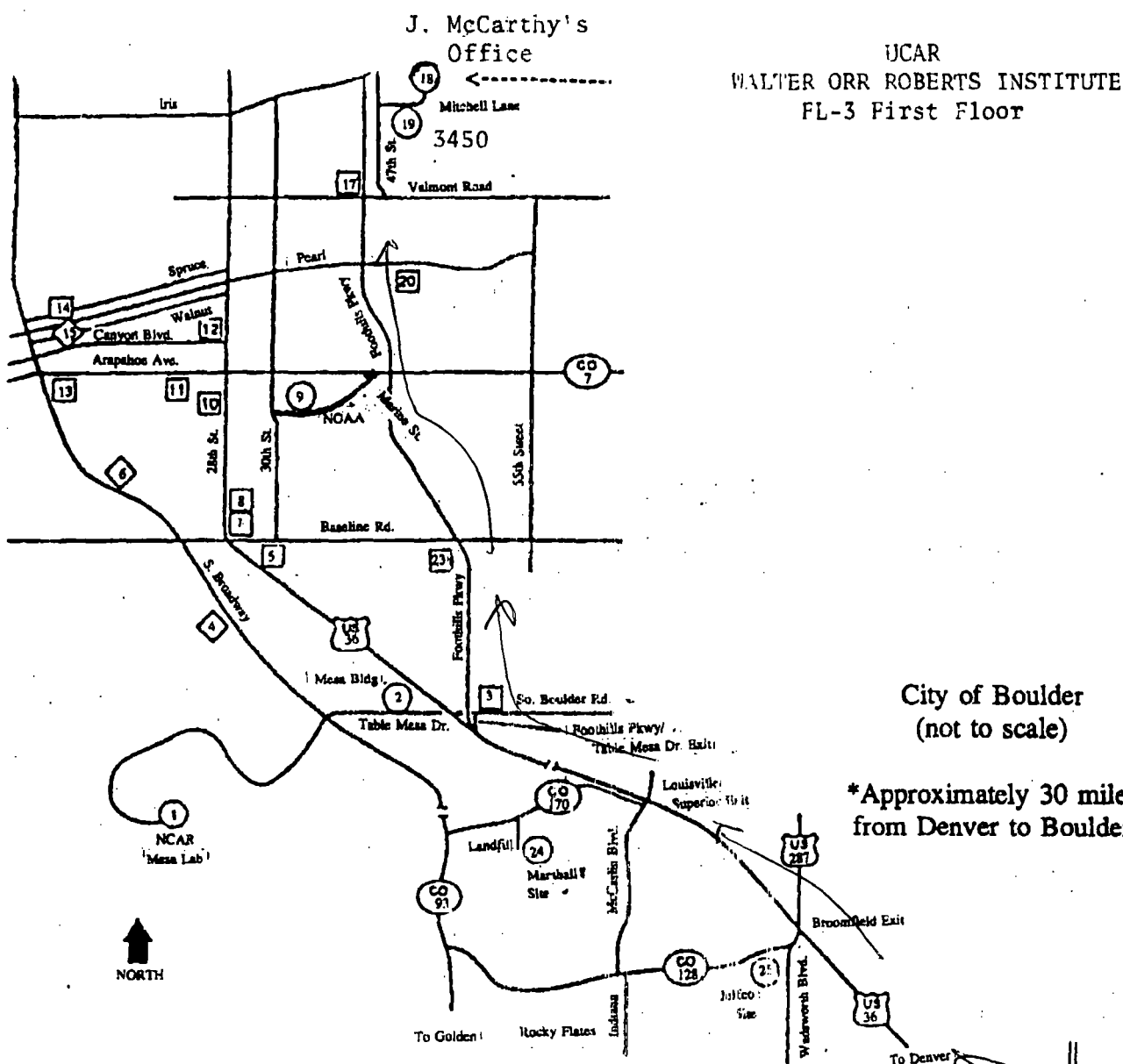
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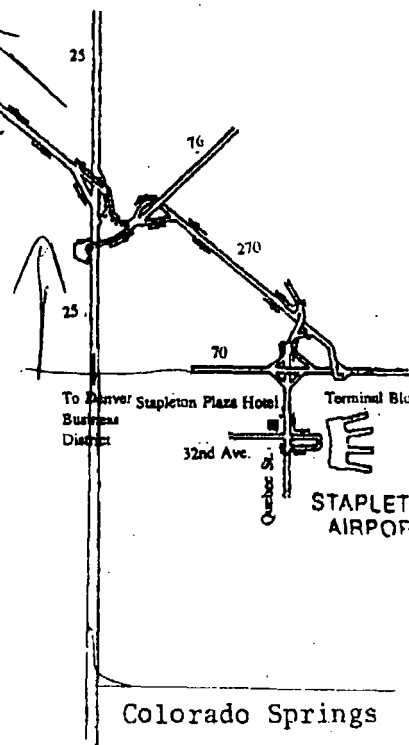
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April 5, 1994

Mr. Johns is interested in a briefing on what is known about the origins and theories regarding the daily, weekly, and yearly migrations of the jet stream over the United States, including the degree to which those migrations are correlated with the variation of weather patterns experienced in the U.S. in the recent past.

He is also interested in whether the migrations of the recent past have exceeded the magnitude, range, or other variables in the last decade. If so, what are the reasons or theories as to the causes? Also, what research is the U.S. doing on this subject? Where is it being done? Is there any international research being done, and if so, where?

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SCIENCE BRIEFS

Science & the Environment

The earth's boreal forests are believed to be one of the more sensitive regions to climate change. An international, interdisciplinary study this summer will utilize NCAR's turboprop Electra aircraft. Its principal mission will be to measure surface exchanges of energy and trace gases across the Canadian boreal forest. The goal of the study is to improve understanding of the interactions between the boreal forest biome and the atmosphere in order to clarify their roles in global change. The information will be used to validate biophysical models which describe the absorption and partitioning of energy at the surface and will develop and validate remote sensing algorithms to transfer understanding of surface processes from local scales out to regional scales.

**Mesoscale and Microscale Meteorology
Division
February 1994**

The Climate System Model Project has been given highest priority for development at NCAR in FY 94. The project, which will dramatically contribute to climate-related research, will focus on building a state-of-the-art coupled atmosphere ocean-land-snow-ice model. After testing, the model will be used for a wide range of climate-research problems - global warming, glacial-interglacial transitions, carbon cycle and climate effects of volcanic eruptions.

**Climate and Global Dynamics
Division Newsletter/Winter 1993-94**

Vol 2, No 1, March 31, 1994 Science and Technology

Researchers recently conducted a major field program studying the cause of aircraft icing. The Winter Icing and Storms Project (WISP), involving 25 researchers from NCAR's Research Applications Program, the National Oceanic and Atmospheric Administration (NOAA) and several universities, is designed to search for the secrets that cause supercooled water droplets and ice crystals to form in clouds. Before meteorologists can better predict aircraft icing, they need to understand its cause. Tiny supercooled water droplets, suspended in air below 32° F, freeze almost instantly when they encounter a hard surface such as an airplane, causing ice to accumulate. The study is focusing on the origins of in-cloud ice. The WISP team is working with the FAA, NOAA's Forecast Systems Laboratory and the National Aviation Weather Advisory Board on a new aircraft-icing forecast system. The project will also involve the United Airlines ground operations at Denver's Stapleton International Airport, by looking at improving airport de-icing efforts.

**Research Applications Program
NCAR News Release
March 25, 1994**

Two NCAR scientists have produced a 17-minute video which follows the evolution of the sun's internal rotation and magnetic field, based on a model created by the solar researchers. The video was sent out

to all subscribers to the November 1993 issue of the *Astrophysical Journal* and is among the first solar research to be produced as an animated journal release. The visualizations created out of the scientists' model reveal a twofold structure in the sun's internal rotation. The animation enhances theorists' understanding of their calculations. Being able to watch the rotation of the sun in animation allows for better understanding of the scientists' calculations and theories. The video is available through the *Astrophysical Journal* or the NCAR library.

**NCAR Staff Notes
March 17 1994**

Representatives from industry and the atmospheric science community met for a two-day workshop in Boulder at the University Corporation for Atmospheric Research. Participants exchanged views and information on the present state of climate and weather science and discussed the needs of the major industrial sectors. The workshop was convened jointly by UCAR's Walter Roberts Institute and the Office for Interdisciplinary Earth Studies. The overriding goal of the workshop is to promote long term collaborative relationships between industry and the atmospheric sciences and to help guide and accelerate the application of climate and weather related research to industry needs. Representatives from various industries, which included utilities, petroleum, transportation and automotive, participated in the program.

**Office for Interdisciplinary Earth
Studies and the Walter Orr Roberts
Institute
March 1994**

A patent for a novel system of measuring metabolic gases, such as methane from cattle, has been

issued to a senior scientist at NCAR. Methane is believed to contribute to a gradual global warming as it accumulates in the earth's atmosphere. Cattle are thought to be a significant source of methane. The invention consists of a harmless cowbell-sized, stainless steel canister attached to a cow's leather harness. The cow is fed a capsule that releases a volatile tracer gas at a known rate. Since the tracer gas is emitted through the cow's mouth in the same way that metabolic gases are released, scientists can use the tracer to calculate the rate of methane emission and monitor the amount of methane that cattle emit into the atmosphere.

**NCAR News Release
February 11, 1994**

A patent for an energy-saving, versatile, flow control sensor system has been granted to two NCAR scientists. The closed-loop sensor system monitors the flow of gas or liquid in its path and dynamically varies the pump's speed of operation in order to maintain a constant flow at a rate selected by the user. The system was developed to provide scientists with the precision not found in previous air-sampling devices available commercially. A working model of the flow controller has been used at NCAR in several experiments. While manufacturing costs have been kept very low, results have been outstanding. The system has potential additional applications, such as air pollution-monitoring equipment, ink-jet computer printers and kidney dialysis machines.

**Atmospheric Chemistry Division
Signal Newsletter
March 1994**

Science and Education

Over 50 high school students participated in the 1994 Colorado Computational Science Fair sponsored by Colorado State University and NCAR's Scientific Computing Division. The fair was the first of its type in Colorado. Its purpose was to provide an opportunity for students to exhibit their science projects, which were designed to solve a science problem by using a computer. The fair offered demonstrations on Internet tools, as well as information on Internet programs serving the K-12 audience.

**Scientific Computing Division
March 1994**

Several NCAR scientists are part of a five-year project that will encourage the development and application of statistical techniques to the problems faced by many scientists. A new geophysical statistics program, sponsored by the Mathematical Sciences Division of the National Science Foundation, is an exciting opportunity to entrain a cadre of much needed statistical experts into the research on atmospheric and climate problems of importance to science and to society. Besides encouraging interactions between scientists and statisticians at NCAR, an important mission of the project will be to facilitate an exchange of ideas and to interest students in problems involving statistics and modeling and analysis of the climate system.

**Climate and Global Dynamics
Division Newsletter
Winter 1993-94**

For more information on these or other science news updates at UCAR/NCAR, contact Laura Curtis, Office of Government Affairs, (303) 497-2106. NCAR is sponsored by the National Science Foundation.

Phenomenon Examined in SIRS Print and CD-ROM

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El Niño might seem to be a climatic "bad guy" bringing destructive weather patterns. Yet research at Florida State University and at the University of Arizona and U.S. Geological Survey Office in Tucson shows that abnormal rains associated with El Niño reduce wild fires. El Niño also puts a lid on Atlantic tropical hurricanes. "When it suppresses forest fires and hurricanes, El Niño is actually a 'good guy,'" O'Brien observes.

"The El Niño Climate Connection," by Robert C. Cowen, Christian Science Monitor, Jan. 29, 1992. From **SIRS Print Science Series** or **SIRS Researcher CD-ROM**.

The weather too can affect the delicate ecosystem of the Channel Islands. The recent El Niño caused the death of an unusually large number of seals, sea lions, pelicans, and other marine life. El Niño dramatically reduced sea bird nesting and the number and size of seal and sea lion pups was much smaller than normal. However, it produced a banner year for whale watching in the sanctuary. With the population explosion of Krill, small shrimp-like crustaceans, an unprecedented number of whales came to feed. Mild winds moved warm surface water away and caused nutrient rich deep water to upwell and reinvigorate the food chain.

"Channel Islands National Marine Sanctuary," by Justin Kenney, Mariners Weather Log, Spring 1993. From **SIRS Government Reporter CD-ROM**.

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National Center for Atmospheric Research/ Learning About Science Easily and Readily Series.

The cover story is a shortened version of a LASERS article by the same title: "Children of the Tropics: El Niño and La Niña." You can get a copy of it by writing to NCAR Outreach, P.O. Box 3000, Boulder, CO, 80307.

Much of the information in this newsletter was drawn from "General Characteristics of El Niño-Southern Oscillation," by Kevin Trenberth, in *Teleconnections, Linking Worldwide Climate Anomalies*, edited by Michael Glantz, Richard Katz, and Neville Nichols (Cambridge University Press, 1991).

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SCIENCE NOW

MARCH 1994
VOLUME 1, No. 3

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Children of the Tropics: El Niño and La Niña

For many years, coastal residents of Peru have noticed a strange feature of the eastern Pacific Ocean waters that border their home. This region of tropical yet relatively cool water is host to one of the world's most productive fisheries and a large bird population. In the first months of each year, a warm southward current usually modifies the cool waters.

But every few years, this warming starts early (in December), is far stronger, and lasts as long as a year or two. Torrential rains fall on the arid land; as one early observer put it, "the desert becomes a garden." Warm waters flowing south bring water snakes, bananas, and coconuts from equatorial rain forests. However, the same current shuts off the deeper, cooler waters that are crucial to sustaining the region's marine life. Fisheries can be decimated and the economy suffers.

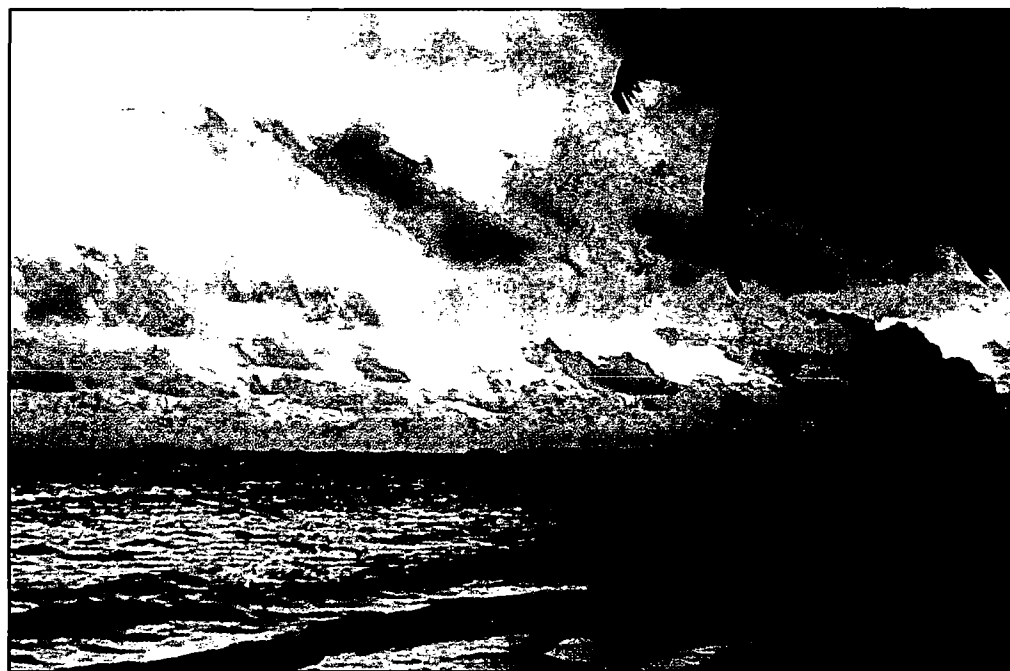
This is El Niño, "the Christ child," so named because of its frequent Christmas appearance. Once thought to affect only a narrow strip of water off Peru, it is now recognized as a large-scale oceanic warming that affects most of the tropical Pacific. The meteorological effects related to El Niño and its counterpart, La Niña (a cooling of the eastern tropical Pacific), extend throughout the Pacific Rim to eastern Africa and beyond.

El Niño is normally accompanied by a change in atmospheric circulation called the Southern Oscillation. Together, the

ENSO (El Niño-Southern Oscillation) phenomenon is one of the main sources of year-to-year variability in weather and climate around the world. Since recognizing some 25 years ago that the oceanic and atmospheric parts of ENSO are strongly linked, scientists have moved steadily toward a deeper understanding of ENSO. Climate forecasters have taken the first steps toward predicting the onset of El Niño and La Niña events months in advance.

The presence of El Niño has been correlated with a number of wide-ranging atmospheric events. Some of the best-established effects are enhanced rainfall over the central Pacific, Peru, Ecuador, and the southern United States and drought in Australia, southern Africa, and northeastern Brazil. ENSO events have also been associated with warm winters in the former Soviet Union, mild winters in western Canada, and cool summers in northeast China, and they have been blamed for contributing to the collapse of the Peruvian anchovy fishery, the rise of the Chilean sardine fishery, and changes in the salmon fishery off the coast of the U.S. Pacific Northwest.

If scientists can better predict ENSO events, countries that are affected by them can prepare for drought and subsequent economic and health impacts. Even countries that are not directly affected by El Niño events can benefit from accurate predictions. For example, Kenya would want to know how its competitors in the world coffee trade—Brazil, Southeast Asia, and Ethiopia—have been affected by ENSO.



The tropical Pacific releases tremendous amounts of energy into the atmosphere as heat and moisture and impacts the global climate; two phenomena generated by the energy in the Pacific are El Niño and La Niña.

Photo by NCAR

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The Basics of ENSO

It was the atmospheric part of ENSO—the Southern Oscillation, or SO—that first attracted the attention of scientists. Sir Gilbert Walker documented and named the SO in the 1930s. Other persistent patterns of high and low pressure had been previously noted in the North Pacific and North Atlantic; thus, the “southern” in SO.

The clearest sign of the SO is the inverse relationship between surface air pressure at two sites: Darwin, Australia, and Tahiti in the South Pacific. The pattern reverses every few years. It represents a

standing wave or “see-saw”—a mass of air oscillating back and forth across the International Date Line in the tropics and subtropics.

This one-dimensional picture was extended vertically by renowned meteorologist Jacob Bjerknes in 1969. He noted that trade winds across the tropical Pacific flow from east to west. To complete the loop, he theorized, air must rise above the western Pacific, flow back east at high altitudes, then descend over the eastern Pacific. Bjerknes called this the Walker circulation (in honor of Sir Gilbert); he also was the first to recognize that it was intimately connected to the oceanic changes of El Niño and La Niña.

The persistent easterly trade winds that blow throughout the tropics are a key ingredient in the ENSO process. Such winds push water toward the western Pacific. The sea level in the Philippines is normally about 60 centimeters (24 inches) higher than the sea level on the southern coast of Panama. The trade winds also allow the westward-flowing water to remain near the surface and gradually heat. This gives the water’s destination—the western Pacific—the warmest ocean surface on earth. Usually above 28°C (82°F), parts of this pool are sometimes as warm as 31.5°C (89°F). The persistent oceanic heat surrounding Indonesia and other western-Pacific islands leads to frequent thunderstorms and some of the heaviest rainfall on earth. During an El Niño, this cycle changes; the trade winds weaken, allowing the pool of warm water to flow eastward toward the coast of South America.

ENSO Variations

Data reveal that ENSO is a regular yet highly variable phenomenon. The strength of the events, as judged by the pressure anomaly (variation from normal), varies greatly from case to case. The strongest El Niño in the past century occurred in 1982–83. Its effects included torrential storms throughout the southwest United States and Australia’s worst drought this century. Sometimes the warm waters generated by an El Niño flow all the way across the Pacific. The 1982–83 event increased surface water temperatures near Peru by up to 4°C



Among the many global phenomena connected to the El Niño-Southern Oscillation are Asian monsoons.

(7°F). In the much weaker event of 1986–87, the warm water flowed eastward only as far as the mid-Pacific (near 170°W) and raised the temperatures there a modest 1°C (2°F) or so. In still other cases, warm anomalies first appear offshore of Peru and then progress westward to meet the pre-existing warm pool.

El Niño and La Niña events have a tendency to alternate about every two years, so the average time between El Niños is four years. However, the time from one event to the next can vary from two to ten years. Sometimes El Niño and La Niña events are separated not by their counter-

parts, but by rather normal conditions.

Some researchers are using computer models to attempt to reproduce the physics of the ocean and atmosphere as they evolve during ENSO events. In 1990, a milestone was reached when the El Niño beginning late that year was successfully predicted months in advance by a computer model at the Lamont-Doherty Earth Observatory of Columbia University. Soon afterward, in 1992, NCAR produced the first model to show the evolution of ENSO-like behavior in an atmosphere containing twice the carbon dioxide of the present (a state likely to be reached by the year 2050). The model indicates that the rainfall anomalies connected to El Niño and La Niña may become stronger in a global-warming scenario.

What are the remaining obstacles to predicting El Niño and La Niña? One is to better understand their quasi-cyclic yet variable beginnings and endings. The factors leading to the end of an El Niño event are not yet entirely clear, as evidenced by the recent failure of computer models to predict the end of the El Niño that began early in 1991. The Lamont-Doherty model called for the event to end in 1992. It continued until late 1993, making it the longest-running El Niño in half a century.

Improvements in tropical-ocean observation will help advance research on ENSO. Buoys that measure ocean temperature to a depth of up to 500 meters (1,650 feet) are now moored throughout the tropical Pacific. A giant field program was mounted in the western Pacific in late 1992 and early 1993, the Tropical Ocean and Global Atmosphere Program’s Coupled Ocean-Atmosphere Response Experiment. The wealth of data from that program and others like it, and from long-term moored instruments, will help scientists better understand the tropical Pacific waters.

These lines of research point toward the day when ENSO events can be reliably predicted months ahead of time. Such information could be of great benefit in planning for drought, flood, and temperature extremes and in mitigating the associated pain and damage. If we cannot hope to control the effects of ENSO, there is real hope that we can understand and forecast its on-off switch.

Bob Henson

Scientists Study Ocean-Atmosphere Interactions

Heat and humidity, mosquitoes, and malaria plagued the more than 700 scientists, students, and specialists studying ocean-atmosphere interactions near Townsville, Australia in 1992 and 1993. Toilets didn’t flush and showers wouldn’t shower, but the dedicated people involved in the Tropical Ocean and Global Atmosphere Program’s Coupled Ocean-Atmosphere Response Experiment (TOGA COARE) persevered.

Researchers from more than 15 nations including the United States, Australia, France, Japan, China, and the United Kingdom, measured temperature, moisture, precipitation, and mixing in the atmosphere. They used satellites, weather balloons, and specially equipped airplanes, ships, and buoys to better understand the engine that drives the global climate.

Energy from the sun drives large-scale atmospheric motions that determine global and regional climate. Because solar radiation strikes the earth most directly near the equator, the equatorial oceans absorb most of this energy. The oceans release much of the energy to the atmosphere as heat or moisture. In the atmosphere, the upward movement of warm, moist air transports energy, releasing heat when water vapor condenses into cloud droplets and raindrops.

Computer models and historical data indicate that a particularly important region is the western Pacific warm pool northeast of Australia. This warm pool, which covers more of the earth’s

surface than the continental United States, is a vast reservoir of warm water (consistently higher than 28°C or 82°F). Up to a half-meter (200 inches) of rain falls there as part of an intense convective process that transfers heat to the upper atmosphere and some incoming energy, but trap outgoing energy. This exchange of energy between the warm water and the atmosphere appear to induce climate variation beyond.

Researchers are using the enormous amount of data gathered last year to better understand the global climate. Projects like TOGA COARE, scientists are asking questions: How do the ocean and atmosphere interact in the global system to produce variations in climate? Can we understand this complex system? Can we predict regional climate variations such as the El Niño stormy periods months to years in advance? Can we predict climate variation, can we then assess its impact on human affairs, including loss of life and property?

Climate variations such as El Niño and La Niña have human affairs, including loss of life and property. With analysis of data from the TOGA COARE, researchers will improve their ability to make predictions of such variations for the future.

ACTIVITY

Make a Model of El Niño

Using hot and cold water, cooking oil, and a blow dryer or fan, you can model the El Niño phenomenon in your classroom. The two modelling options included in this activity demonstrate the difficulty scientists face in modelling complex systems.

Materials:

- A blow dryer or fan
- cold water in container
- cooking oil
- hot water in a container
- food coloring
- funnel
- glass baking dish or clear plastic shoebox

Safety Warning to Teachers: Please stress to your students the importance of keeping an electrical appliance, such as a blow dryer, away from water. Electric shock can occur when the appliance is in contact with water even if the appliance is switched off. Always unplug the appliance after use. If the appliance falls into or is in contact with water, unplug it immediately. Do not reach into water to retrieve the appliance unless it is unplugged. To reduce risk of electric shock, provide close supervision for students, or demonstrate the El Niño model for the entire classroom.

Procedure:

Measure out three to five cups of very hot and very cold water in separate containers. Add different colors of food coloring to each

container. (Red for hot water and blue for cold water.) Pour the water into a shallow dish or shoebox. Be sure the water in each container represents a different temperature. T tepid water will not work effectively. Carefully add the cold water to the bottom of the dish. This two layer effect represents El Niño. The cold water prevents the cold, nutrient-rich water from rising. Without that cold water, the fish die. The temperature variation of the ocean surface is the accurate ratio of warm water to cold water. Pour 3/4 full of colored water (temperature of the water) into a layer of oil over the surface. This will show the temperature gradient, but does show the circulation pattern found in the Pacific.

To illustrate the normal condition of the ocean, pour the hot water on to a no-heat setting or the fan on. The hot water will flow across the length of each dish. The cold water will be pushed to one side and the cold, nutrient-rich water will be pushed to the other side. The trade winds accompanies an El Niño. The hot water at different depths of water and oil and the cold water will creep back over the surface. What does the circulation pattern look like?



Project LEARN

UPDATE

Vol. 2, Number 1

"The knowledge of the world is only to be acquired in the world, and not in a closet." The Earl of Chesterfield

February 1994

Evaluation Report Finds that Project LEARN Impacts Teaching Methods and Curriculum

Caroline Hanson

In his second evaluation report of Project LEARN, Dr. Ronald Anderson of the University of Colorado Education Department summarized the second year of the project as a "clear success" and indicated that the experience teachers are gaining at NCAR is impacting their classrooms.

"The participants continue to grow in their understanding of the atmospheric sciences and how to incorporate this understanding into their teaching," he wrote. "More activities of this nature continue to be incorporated into their teaching. The project staff continues to identify productive means of moving the project forward in meetings its goals."

Anderson's report was written after visiting school sites, interviewing project teachers, observing inservices developed by teachers, and meeting with project staff. The report is part of an ongoing assessment of the program for the National Science Foundation; he will write a summative report for the project's conclusion in January of 1995.

In his interaction with project participants Anderson tried to determine what specific changes have occurred in the participating school districts as a result of the project. He found that teachers are making significant changes in their teaching.

"There are many testimonials to the use of new teaching ideas, new and more frequent laboratory activities, and a new sense of excitement about science on the part of both teachers and students."

He also found that in some districts the science curriculum has changed as a result of the project. "Essentially all teachers report significant changes in what they are teaching in their science classes, especially in terms of incorporating atmospheric science content that had not been there in the past. It is clear

"The professional judgment of the participating teachers—as well as some principals who were interviewed—is that the program has been very valuable for them, their schools and their students."

that the atmospheric sciences provide an abundance of material that relates to other basic science concepts; it can be used to show applications of its basic science and it provides excellent material for integrating science concepts across disciplines."

Districts in which the most substantial changes have occurred are influenced from changes in the state curriculum framework or restructuring at the school or district level. Anderson indicated that the project would have a greater impact if the collaboration extended beyond the classroom teachers to include school or district leaders.

Two aspects of the project which Anderson found to be important in having an impact on the participating schools were multiple year participation of the teachers and their involvement in conducting inservice education for other teachers. Teachers indicated that these two factors contributed to their ability to disseminate atmospheric science content.

Anderson also asked teachers whether they found the project valuable to themselves, their students, and their schools. The response was positive; teachers offered specific examples of new approaches they used in their classroom. "Although there obviously are variations in how teachers are influenced by their participation in the project, all teachers interviewed were convinced their participation was worthwhile and was having a positive impact on their teaching."

The report cited one principal who recognized an attitudinal change in the teachers who participated in Project LEARN. He noted that the teachers taught differently and that the teachers had a positive impact on their colleagues and the school. Anderson wrote in his report, "The professional judgment of the participating teachers—as well as some principals who were interviewed—is that the program has been very valuable for them, their schools and their students."

The deadline for the March Issue is Feb. 28. Send in contributions.

Resources

Authentic Assessment Information for Science Concepts on CD-Interactive

The National Science Teachers Association and Philips Interactive Media of America are collaborating to develop an interactive software system that will track and store assessment information as student progress through a series of activities on 40 science concepts. The prototype assessment project, available on CD-Interactive, measures the degree of mastery of the concept density in grades seven through ten. Students are led through ten levels of activity, and the computer tracks and stores student actions and responses, which can later be printed out for teacher use. The collaborators hope that the system, when fully operational, will drastically lower costs for assessment. To learn more, write Philips Interactive Media of America, 1111 Santa Monica Blvd., Suite 400, Los Angeles, CA 90025; (310)444-6600. (Information from *Science Activities Magazine*.)

DOE's Nuclear Waste Curriculum Available for Teachers - Free!

Teachers interested in teaching about scientific and social issues related to the management of spent nuclear fuel and high-level radioactive waste can write for a copy of the Department of Energy's resource curriculum titled "Science, Society, and America's Nuclear Waste." The curriculum is free and is designed for grades 8 - 12. The curriculum is broken down into four modules that include teacher and student guides, videotapes, activities, and computer software. For more information call 1-800-225-6972, or write: OCRWM Information Center, Attention: Curriculum Dept., P.O. Box 44375, Washington, D.C. 20026.

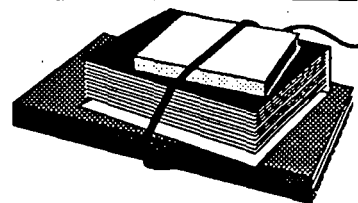
Middle Education Conference to be held in Boulder after Project LEARN

If you have some extra money and want to extend your stay in Boulder this summer, you might be interested in attending the "Fifth Annual Nuts and Bolts of Middle Level Education" from July 24-28. The conference will feature top middle school presenters from around the country, 60 topics and 150 sessions, and major strands of teaming, advisory, curriculum, urban issues, heterogeneous grouping, block scheduling, authentic assessment, restructuring, outcome-based education, diversity, and service learning. The conference reg-

istration is \$345 and the conference will be held at the Clarion Hotel near the university. For a brochure and more information contact Walt Grebing, Conference Director, 1437 Dunsford Way, Broomfield, CO 80020. (303) 466-2387.

Earth Day Projects Publication Available

Earth Day in Your School and Community offers more than 60 projects in an environmental curriculum written by and for teachers. The activities are designed to be integrated into any subject. Send \$10 plus \$2.90 for postage to Heartland All Species Project, 201 Westport Road, Kansas City, MO 64111. (816) 756-5686.



Project LEARN UPDATE

Project LEARN Update is published eight times a year by Project LEARN staff for participating teachers, their district administrators and staff of The National Center for Atmospheric Research. Project LEARN is a joint effort of the National Science Foundation and NCAR. The goal of the three year project is to improve understanding of the atmospheric sciences and related mathematics and to improve science teaching methodology through experiential training. For questions or comments about the program or newsletter, please write to: Project LEARN, P.O. Box 3000, Boulder, CO, 80307 or call (303) 497-8107. You can also contact us via Internet: chanson@ncar.ucar.edu.

Newsletter Editor: Caroline Hanson

Program Directors: Joyce Gellhorn,
Carol McLaren

Project Scientist: Pat Kennedy

Odds and Ends

Chris Ferguson and his wife have moved. Be sure to note his new address and phone number in your directory: 14511 Little Willow Walk
Houston, Texas, 77062.
(713) 480-8618.

Chris also wanted to share that the "Comet at You" lab developed over the summer worked really well. Chris is also helping to develop a curriculum with some NASA scientists called "Mission to Mars." He will be writing the curriculum through the spring.

Pamela Strand is now hooked up to Internet. You can contact her using pamelastrand@delphi.com.

Darlene Black was nominated for a Presidential Award in Science Teaching. Congratulations!

Darlene and the other members of her team and Judy Lee from the CAPE team presented Project LEARN materials at the CAST conference November 6. About 45 teachers showed up for the training, an impressive number since the presentation, called "The Dyanmic Atmosphere," was on the final afternoon of the conference. The teacher participants were pleased. **Judy Lee** presented solar activities and information on UV rays. The NCAR introduction tape was used and the turbulent orb was showcased as a way to demonstrate currents and wind patterns. **Chris** demonstrated the pickle lightning and everyone else shared successful lessons and ideas for resources. The team plans to give the same inservice at the Houston Area Middle School Conference in the spring. Darlene also wants to contact the Education Department head at the University of Houston to see about doing an inservice for teachers there.

Judy Lee has been working with Amber Maier, a teacher intern, to enhance the activities in the ozone module. Her

students wrote to Whamo, NCAR scientists, and television meteorologists with the help of an English teacher. She hopes to hear from Whamo because one of her students designed a Frisbee that can be used as a uv indicator that will tell people when it's time to apply some sunscreen.

Texas Students Work with Younger Peers to Measure Ozone Levels in Their Community

Judy Lee's class is presently conducting a Schoenbein paper test for the Texas City Area. The eighth grade class will work with first and fourth grade classes to test the air in

and around Texas City. Her science classes became partners with Roosevelt Wilson Elementary students for the lab. The eighth grade student is responsible for introducing and conducting the lab with the elementary students.

Judy's students will explain that they are testing for tropospheric ozone in the city and school. Students will grow bean plants and place rubber bands around different locations to test for tissue damage. The idea came from two eighth grade students, Shannon Johnson and Grace Owens. The girls researched the topic of ozone and found unique ideas to use. Shannon's lab contains Ziploc baggies, three large lima beans, one wet paper towel, and staples. Her idea was to see if the leaves and the roots would grow correctly. She placed a paper towel in a Ziploc bag and stapled it down the center. She next added the beans and water. Shannon's idea was to see if root damage occurred at the same time as leaf damage.

Grace Owens has a book of labs that she shared with the class. She found an ozone test using rubber bands in a shoe box that is placed out of direct sunlight. Since the first trial she learned to make sure the rubber bands are all the same size.

Two first grade classes planted beans in cups and in the Ziploc bags. The fourth grade classes kept a diary and plotted the growth of the beans with the eighth grade students. All of the students took Schoenbein paper home to be exposed to the air where they live. The data will be plotted on the Texas City map and students will connect areas of equal concentration using contour lines. The final step will be to present the information to the Air Quality Control Board of the State of Texas.

Judy wanted to be sure to let scientists and Noelle know that the ozone lessons have touched many lives.

Caroline Hanson gave birth to Nathan Thomas Hanson on January 3 at 11:20 a.m. He was six pounds, ten ounces at birth and is changing before his mother's bleary eyes.

Mom and baby are doing fine; remember that mom will only be in the office part time through the spring. If you need to talk to someone call Joyce or Carol on Tuesdays and Thursdays at 303-497-8108 or 8109.

Remember to mark July 11-22 on your new 1994 calendars as the dates for the summer workshop. It's not too early to start thinking about how you'd like to get here (drive or fly) and also the days you'd like to travel.

Ask A Scientist

Students Want to Know More About UV and Ozone

Questions were submitted by Judy Lee's students.

- What does relative humidity have to do with false readings of high ozone?

Response from scientist Ken Davis of the Microscale and Mesoscale Meteorology Division:

I'm guessing that the question is related to using Schoenbein paper (paper soaked in a starch - potassium iodide mixture) to measure ozone mixing ratios. First realize that this is an inexact measurement technique which is sensitive to the process used to prepare the paper. It is probably best to trust only qualitative results found using this technique, and to treat even those results with suspicion. Exact measurement techniques are very expensive. Learning that science can be messy and full of uncertainty is a very important lesson.

Second, relative humidity does have an effect on measurements using Schoenbein paper. In a way which I do not fully understand, moist Schoenbein paper changes color more readily than dry Schoenbein paper. The ozone module activity written by Noelle Fukushima describes the chemical reactions which we assume are taking place to create this color change. The first reaction involves water, so presumably the more water present, the more likely the reaction is to occur. A basic principle of chemistry is that a reaction rate is proportional to the concentration of reactants.

Chart B of the "Schoenbein Paper" activity shows measurements of the effect of relative humidity on Schoenbein paper ozone measurements for a particular paper preparation process. The graph was taken from a paper published by the American Meteorological Society in the journal *Monthly Weather Review*. This chart indicates that even when relatively little ozone is present, Schoenbein paper can show a large color change if the relative humidity is high. Note that we have yet to locate an actual color print showing what colors correspond to which Schoenbein number - Chart A is our guess.

- What severe weather is characteristic of the Texas City/Galveston, Texas area?
- How can we protect ourselves from UV rays?
- Are there more UV rays in Texas than there are in Colorado?

Response from scientist Pat Kennedy of the Climate and Global Dynamics Division:

I'm glad to see that you all are studying uv rays, and I'll

throw in my \$0.02 worth. In hand are questions from Arnulfo, Manuel, Eric, Courtini, Ryan, Shannon, Teri, and Daniel regarding uv rays in Texas. Rest easy that Texas at sea level is better protected by the full atmosphere than we Coloradans at high altitude. In any case, the usual precautions should be taken: sunscreen, sombrero, and a siesta between 10 a.m. and 2 p.m. The Mexicans had this figured out years ago! And we should follow them. Also, if you're a blondie you have less natural protection than morenos. The skin cancer "capital" of the U.S. is Tucson, Arizona, due to its very clear skies year 'round and moderate altitude.

In your area, the major weather events are the occasional hurricanes in late summer and early fall. Then you get some tornado outbreaks in spring, as the warmer tropical air pushes northward to eventually cover the U.S. by summer. Overall, you all live in a humid climate and vegetation is lush, due to the closeness of all that gulf of Mexico water. All that water also acts as a natural moderator of extremes. In interior parts of the continent, the climate has more extremes. Look up some climate data for Winnipeg a few thousand miles due north of you and NOT near any large bodies of water. There you have very cold winters and hot summers.

- What is the most recent information about ozone and uv rays?

Response from scientist Bill Mankin of the Atmospheric Chemistry Division:

For about 20 years, scientists have been concerned about the possible loss of ozone due to reactions with manmade chemicals such as the nitrogen oxides that are emitted by high flying aircraft and chlorine from long lasting chemicals such as CFC's (chlorofluorocarbons, a kind of chemical that contains chlorine as one of its components, and which lasts so long before breaking down that it can get to altitudes where the ozone is, about 20 miles up). It was originally thought that the loss of ozone would be very gradual and occur all over the world. In 1985, it was discovered that ozone was going away over Antarctica in the springtime (October) much faster than has been expected. Experiments showed that this was due to chemical reactions on clouds that converted harmless chlorine compounds to ones that can destroy ozone. Before the Antarctic ozone hole was discovered, no one had thought to include clouds in the calculations.

Our concern about ozone is more serious in northern midlatitudes, where the U.S., Canada, Europe, China, and

Ask A Scientist

Japan are located, because many more people live there. Ozone loss here would expose many people to extra ultraviolet radiation. Uv radiation has many effects, some of which are harmful to people.

In 1991, a large volcano in the Philippines, Mount Pinatubo, erupted, putting large amounts of a chemical sulfur dioxide into the stratosphere. Chemical reactions turned this chemical into clouds of tiny droplets of sulfuric acid. Some of the same cloud chemical reactions that produce harmful chlorine in Antarctica can also occur on these droplets, producing harmful chlorine compounds all over the world.

Measurements by satellites have shown that last winter and spring ozone over northern midlatitudes (including the U.S.) was lower than had ever been measured before, approximately 15% below normal. The usual variations due to weather patterns, solar variations, etc. are about +/- 5%. Most scientists (but not all) believe that this is due to the combination of high levels of chlorine (due to all the chemicals we have produced and released to the atmosphere) and the aerosol particles (sulfuric acid droplets) in the stratosphere from Mount Pinatubo. Unfortunately, the satellite instrument called TOMS (Total Ozone Mapping Spectrometer) that measured the ozone quit working last May, and the data from its replacement is not yet available. (So you won't be upset about the TOMS quitting, I should tell you that it was only supposed to last 5 years and it lasted 13, giving us daily global maps of ozone.) So, I cannot tell what has happened for the last six months. Probably the ozone will get a little closer to normal as the aerosols from Mt. Pinatubo disappear, but it will probably not get completely back to normal for many years.

We are doing the right thing to "fix" the ozone layer by stopping using the chemicals that are causing the problem, but it will take many years, perhaps 50-100 years, for the chemicals already in the atmosphere to disappear, allowing ozone to return to its undisturbed levels.

Ozone protects us from solar ultraviolet radiation, especially the shortwavelengths called uv-b. These wavelengths cause a variety of bad effects including skin cancer, cataracts, suppression of the immune system, damage to crops, and damage to materials. We do not know what all the effects of reduced ozone are. Some might be beneficial, but we know enough possible bad effects that we do not want to do the experiment of increasing uv-b.

• Why are the uv rays at the south pole affecting animals?

Response from scientist Bill Mankin of the Atmospheric Chemistry Division:

I don't think they are. First, at the south pole there are no animals except for the occasional scientist. There have

been reports of effects on animals, sheep and rabbits, near Punta Arenas, Chile, which is the southernmost city in the world. It is still 2500 miles from the south pole. I do not believe that the effects of illness and blindness in the animals have anything to do with ozone. People see sick animals; they know that the ozone is thinning. Sometimes they jump to conclusions that the sick animals must be caused by the ozone loss. That is not necessarily so. Lots of things make animals sick. Most of the effects that are expected to be caused by ozone loss take years to develop (sunburn is an obvious exception - you can get sunburned in one day). I doubt that the animals have been exposed to enough ultraviolet to cause the types of problems observed. I have not seen any believable evidence that links the animal illnesses to ozone loss. It is possible, but I doubt it.

• What is NCAR like?

Response from scientist Bill Mankin of the Atmospheric Chemistry Division:

I saved this question for last because it is fun to answer. NCAR is a great place to work. I get paid for doing things that are so much fun that if I were rich and didn't have to earn a living, I'd do them just for fun. NCAR is in a beautiful place; Boulder is one of the nicest cities in the country (in my opinion) and having the Rocky Mountains just out the back door is a delight. On a clear day, I can sit in my office and see Pikes Peak which is about 75 miles away. We have deer that wander all around our park like setting, and occasionally we see foxes, coyotes, raccoons. There are even mountain lions in the area, although it is rare to see one since they are shy! The people I work with are nice and fun to be with. We have important work to do that makes us feel as if we are contributing something positive to society.

In my work, I make measurements of the upper atmosphere and study the chemicals that affect ozone. I mostly do my experiments on airplanes. I have flown research flights to both the north and south poles, and have worked in Canada, Mexico, Costa Rica, Panama, Brazil, Argentina, and Chile, as well as in Norway, Sweden, and Iceland. So I get to see a lot of the world, as well as my office. I have been to all 50 states and over 24 foreign countries. Some people might not think that is fun, but there are other jobs at NCAR. Some people write programs for the world's most powerful computers. Others operate radars to study weather or chase tornadoes or hail storms. Some try to predict the climate a hundred years from now; others study tree rings or ice cores to find out what the climate was a thousand years ago. Still others try to find out how the sun shakes or vibrates or whether it is getting brighter. There are all sorts of jobs here, and they are all important.



Project LEARN

National Center for Atmospheric Research
P.O. Box 3000
Boulder, CO 80307-3000

Start Reviewing Modules

By now you should have received copies of the Atmospheric Dynamics and Water Cycle modules. You will shortly receive the other three. Contact your team leader if you want to see a copy of a module if you were not in the Water Cycle or Atmospheric Dynamics group. Remember, you will only get a copy of the module you helped produce, but your team will get a complete set. Please SHARE!

Your task is to review the material, test the materials in your classrooms or those of your colleagues, and make suggestions. Send in any and all suggestions by June 10 so that when you arrive in July you will be reviewing a revised draft. Many of you have made revisions for inservices or created new activities. Send them in so they can be incorporated into a revised copy for general review.

As you review the modules, let us know which materials were gleaned verbatim from other curriculum, both words and graphics, so that Project LEARN can seek out permissions for the materials. You and your districts could be held liable for copyright infringement if you use copyrighted material that is not appropriately credited, so give credit where it is due!

Problems? Suggestions?

Call (303)497-8107

or email to :

chanson@ncar.ucar.edu



To Do List for February:

- ☐ Contact us with questions and feedback.
- ☐ Send in newsletter items from classes, inservices, and meetings or questions for scientists. Next deadline is February 28 for a March newsletter.
- ☐ Test modules and start sending in feedback. All responses are due by June 10.
- ☐ Share resource ideas.
- ☐ Let us know when you are hooked up to Internet so we can get your address out to others.
- ☐ Meet with your team to find out how everyone is doing.

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McCarthy Appointed as Director of Walter Orr Roberts Institute

BOULDER—John McCarthy, a leader in developing weather warning systems for aviation, has been appointed a vice president of the University Corporation for Atmospheric Research (UCAR) in Boulder, Colorado, and director of the Walter Orr Roberts Institute, announced UCAR president Richard Anthes. McCarthy will assume the post on April 1, succeeding the institute's initial director, Radford Byerly, who served during the latter half of 1993, and current interim director Harriet Barker.

A consortium of 61 universities with Ph.D. programs in the atmospheric and related sciences, UCAR manages the National Center for Atmospheric Research (NCAR), which is sponsored by the National Science Foundation.

Founded shortly after the death of Roberts, NCAR's visionary founder, the institute is designed to further the application of atmospheric and related science in the service of society and to help translate the goals and products of that research for policymakers, students, and the public. As a UCAR vice president, McCarthy also will oversee the Corporate Affiliates Program, the Development Office, and the Office of Government Affairs.

"Walt Roberts helped me to understand that it is possible and desirable to bridge the gap between fundamental research and the viable integration of that research into society," says McCarthy. "While many research problems remain unresolved and immature for such a transfer, many domains are ready for this all-important passage.

"As director of the institute, I will be addressing outreach and advocacy on weather and climate issues that have the potential to significantly alter life on the planet, from severe storms—such as hurricanes, tornadoes, blizzards, and flooding rains—to ozone depletion,

pollution, global warming, and other aspects of global change. The institute will establish focused programs in education and outreach, applied research, and technology transfer to address the needs of the public, including students of all ages, decision-makers and policymakers at all levels of government, and the private sector worldwide."

Some of McCarthy's specific goals for the institute include

- Building a small permanent staff, to be supplemented by prominent visiting researchers.
- Pursuing opportunities in the private sector. "In our emerging world economy, business endeavors will play a pivotal role in helping make the world a better, more sustainable one," says McCarthy. "To listen to and work with industry is key to the success of the institute."
- Demonstrating societal benefits of mesoscale weather forecasting and warnings and assessing the costs and benefits of the U.S. Weather Research Program (USWRP), in collaboration with entities such as NCAR's Environmental and Societal Impacts Group. The USWRP is drawing renewed interest among researchers and the federal government.
- Developing international opportunities, particularly in Asia, where McCarthy recently spent four months on sabbatical. "China has the fastest-growing aviation sector in the world," says McCarthy. "There are enormous issues in environmental quality throughout Asia, yet environmental consciousness is low. The opportunities for contribution from our institute are substantial."

McCarthy has directed NCAR's Research Application Program (RAP) since its inception. RAP conducts research on weather that affects aircraft safety. This research is sponsored by the National Science Foundation through an Interagency Agreement in response to requirements and funding by the Federal Aviation Administration's Aviation Weather Development Program.

From 1981 to 1985, he directed the Joint Airport Weather Studies and the Classify, Locate, and Avoid Wind Shear projects, whose discoveries on wind shear and related phenomena led to the creation of RAP to devise and implement detection and warning systems for airports. McCarthy received a bachelor's degree in physics from Grinnell College and a master's degree in meteorology from the University of Oklahoma (OU) before completing his doctorate at the University of Chicago in 1973. He taught at OU from 1973 to 1980. Writer: Bob Henson