

Klaus Wyrтки and El Niño

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When an El Niño is announced, it means a warm current appears in the usually cool eastern Pacific. As part of a global climatic event, occurring on average every three to seven years, El Niño impacts weather around the world. Although El Niño has been known for centuries to people living and fishing along the South American coast, much of our understanding of El Niño dynamics has come about only in the last 35 to 40 years. An interaction between the ocean and the atmosphere, its cycles are not fully understood, and reliable prediction more than a few months in advance lies still in the future.



It was **Klaus Wyrтки**, oceanography professor at the University of Hawai'i from 1964 to 1994, who provided a key piece to the El Niño puzzle that helped to forecast such events by several months. The weak trade winds over the tropical eastern Pacific had been thought to reduce the upwelling of cold water there, resulting in the accumulation of warm water. Wyrтки showed that under “normal” conditions, the trade winds in the Northern and Southern Hemispheres act to pile up warm water in the western Pacific, so that sea level is higher in the western than the eastern Pacific. When the wind field changes during El Niño, warm water surges eastward, a phenomenon he demonstrated with changes in sea level.

Wyrтки has received numerous awards for his research on El Niño and his contributions to understanding ocean dynamics: the Rosenstiel Award, the Maurice Ewing medal from the American Geophysical Union, the Sverdrup Gold Medal from the American Meteorological Society, the Albert

Defant Medal from the German Meteorological Society, the Prince Albert I Medal from the International Association of the Physical Sciences of the Ocean, and the Alexander Agassiz Medal from The National Academy of Sciences.

“Wyrтки was the first to understand that there are large-scale connections over the ocean, such that oceanic events near Peru and Indonesia could be linked together,” says IPRC Director Julian McCreary. “Today, the idea seems so obvious. But in the 1970s it was a tremendous leap. The idea that combining sea level measurements from islands, separated

in longitude by thousands of kilometers, could give a coherent picture about changes in ocean circulation was a great advance in scientific thinking.”

What led Wyrтки to this “tremendous leap”? The story begins in post-war Germany, just after the universities opened their doors to students once more. “I was studying physics and mathematics at the University of Marburg. I knew I didn’t want to be a physicist or a mathematician,” Klaus Wyrтки recalls. “I was looking for applied things... took a course in climatology, read books on meteorology, and discovered that oceanography exists. I loved the sea. During the war, I was in the navy, on

a little escort vessel. The captain treated me like his son. He taught me a lot and sometimes let me run the ship.”

In Spring 1948, Wyrтки followed his dream and studied oceanography with Georg Wüst at Kiel University where he obtained his PhD in 1950 with *magna cum laude*. The years that Wyrтки spent analyzing the Baltic and North Sea water-mass budgets during and just following his dissertation work impressed upon him the astonishing variations that occur in the ocean. Through his work, he realized the power of the winds to influence the ocean, and just how much information sea-level variations provide about changes in ocean circulation.

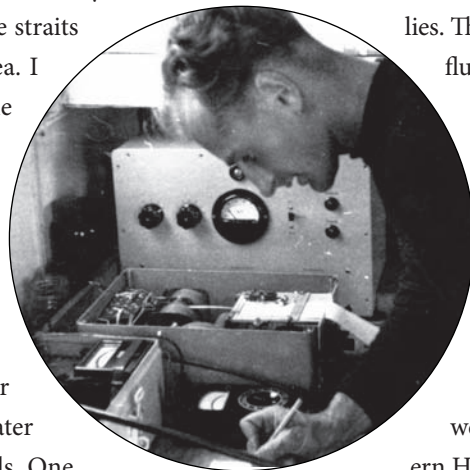
“My first job was at the German Hydrographic Institute working for the British navy. I studied the wind field. Dietrich² gave me the assignment, and we computed the winds over the North Sea. We had wind data for a 50-year period, and we saw how much they varied. I studied how the winds influenced the flow through the Straits of Dover, and how sea

level in the North Sea changed in step. That is where meteorology and oceanography came together for me, right in the beginning of my career.”

“In April 1951, I returned to Kiel to study the water exchange through the Belt Sea, the straits connecting the Baltic with the North Sea. I made many measurements with paddle wheel current meters. I also studied existing long records of sea level and of surface currents from several light vessels. The combination of the short direct measurements and the long time series gave me insight into the fast response of the in- and outflow of water to the Baltic. The dynamics of these water movements were controlled by the winds. One very striking event occurred when large wind-produced seiches of the Baltic resulted in a flooding at Kiel... This research opened my mind to the importance of short, intense events for the circulation and water structure in the ocean. Ever since observing the seiches in the Baltic, I was wondering whether similar events might not happen in the large ocean basins. ... Yes, as I found out later, they do occur, and it is called El Niño.”³

It was many years, however, before Wyrтки turned his attention to the mysteries of El Niño. By then his work had taken him around the world, first to Indonesia (1954–1957), a brief stint in Monaco (where he lived next door to Winston Churchill), and then on to Australia (1958–1961) and Scripps (1961–1964). At Scripps, Wyrтки met the famous meteorologist Jacob Bjerknes, who was spearheading the El Niño research. Wyrтки remembers, “Bjerknes from UCLA often came down to us at the Tuna Research Program, and he talked about El Niño a lot. At the time, I saw El Niño as something unimportant, as a curiosity.”

Only after his move to the University of Hawai‘i and completion of his significant *Oceanographic Atlas of the International Indian Ocean Expedition*, did Wyrтки turn to climate and to El Niño. It was 1971. “The North Pacific Experiment (NORPAX) started, and Namias and Bjerknes wanted to find out how the Pacific Ocean affects North American climate. And I jumped on it. I was intrigued by Namias’ work on how surface temperatures affect the weather downstream over North America, and by Bjerknes’ work on how the equatorial ocean has something to do with these changes.”



Bjerknes had been doing research on El Niño for over a decade. He had determined that El Niño was linked to unusual warm water in the eastern tropical Pacific that extended far to the west and resulted in large-scale weather anomalies. These unusual conditions he connected with fluctuations in the trade winds in the Northern and Southern Hemisphere and to the Southern Oscillation. Bjerknes thought the warm water off the coast of Peru stemmed from less upwelling when the trade winds were weak. In 1969 he concluded: “The maxima of the sea temperature in the eastern and central equatorial Pacific occur as a result of anomalous weakening of the trade winds of the Southern Hemisphere with inherent weakening of the equatorial upwelling.” Bjerknes had not looked at what was happening below the sea surface and to the currents.

The next years whirled Wyrтки into the center of El Niño research. This is how it began: “I had to write a proposal for NORPAX, and I went to my computer programmer Shikiko Nakahara, and said, ‘Shikiko, we have to make a discovery. We have monthly maps in the Indian Ocean Atlas of the depth of the 20°C isotherm (the depth at which the ocean temperature is 20°C). Why don’t you make monthly difference maps for the whole year.’” Wyrтки chose the 20°C isotherm as, in this region, this temperature marks the center of the thermocline, the layer in which water rapidly gets colder. The depth of the thermocline varies greatly and therefore tells oceanographers much about the ocean structure and such things as ocean currents.

“A few days later, Shikiko brought all these maps, and there we saw that in May along the coast of Somalia the 20°C isotherm went up—this was the case all the way from the Arabian Sea to Madagascar—and it went down off the coast of Sumatra. I calculated the change in the level of the thermocline and got a huge volume of water. There must be a current of 15 to 20 Sverdrups between the two coasts and that is not peanuts! (one Sverdrup equals a flow of one million cubic meters per second.) In October, the current flows again. It’s because of the winds. During the transition between the summer and the winter monsoons, the winds are westerly on the equator. They push the water eastward across the Indian Ocean and the water piles up along Sumatra. These jets gave me an explanation for El Niño.”

Between the westward-flowing North and South Equatorial currents, the Equatorial Countercurrent, carrying warm water, flows eastward across the Pacific between about 4°N and 10°N. “I knew from my research that these currents vary during seasons and over years. So when the transport of the Countercurrent is stronger than normal, sea surface temperatures in the eastern Pacific should be higher.” The warm water off Peru during an El Niño, therefore, might not be the direct result of local weaker trade winds and less upwelling in the east, but water that comes across the Pacific from the west.

To confirm his hunch, Wyrtki needed data on the winds and currents in the Pacific. Although daily wind data existed at some islands, there were no analyses over time. He recalls: “I asked our meteorologists, ‘How do the trade winds change?’ and the answer was, ‘We don’t really know!’ I said, ‘We have to know because the trade winds drive the circulation, and so we must know how they vary with time.’ In 1972, about 3 million ship observations in the Pacific Ocean became available from the National Climate Data Center. My graduate student Gary Meyers reduced the data into monthly wind charts. People thought we should stop at the equator... I said, ‘The equator is only a mathematical line. We must include the entire southeast trades.’ That was an important decision. El Niño, it turned out, is connected with events spanning the equator.”

The wind data were ready for use only a year later. The ocean data to demonstrate variations in the Countercurrent were also hard to come by. After the war, tide gauges had been put onto some islands in the Trust Terri-

tories by the United States Coast and Geodetic Survey. The 20 years of tide-level data could be converted into the times series of the sea level that Wyrtki needed. With tide gauges in only four central Pacific locations—two islands located near the northern flank and two islands on the southern flank of the countercurrent—Wyrtki set out to confirm his hypothesis: “Combining the dynamic topography from ship records with the sea level observations from the tide gauges, I developed my method to compute the strength of the equatorial currents in the central Pacific. The high correlation between the transport and the sea level differences allowed me to measure current strength. I found that the currents between pairs of islands undergo large fluctuations. My simple conclusion was that if the Countercurrent runs very fast, it must bring much more warm water to Central America. So I compared over the years the strength of the countercurrent in the central Pacific with sea surface temperatures in Costa Rica, and they agreed wonderfully. Although my measurements were on the other side of the equator, I thought that a very strong countercurrent must be related to El Niño off Peru. That led to my Teleconnections paper, and that’s when I got together with Bjerknes. Bjerknes was absolutely delighted when he saw that... It was a most exciting time.”

In the Teleconnections article, Wyrtki concluded: “The countercurrent carries warm water into the eastern tropical Pacific, and fluctuations in its strength give rise to temperature anomalies off Central America. Periods of exceptionally high transport by the countercurrent in the western Pacific

coincide with occurrence of El Niño several thousand kilometers downstream and demonstrate the existence of teleconnections between events in the Pacific... Such teleconnections have been found in the atmosphere by Bjerknes, but I believe, have not before been established in the ocean.”⁴

At a NORPAX meeting at Lake Arrowhead in 1974, Wyrtki presented his theory on El Niño that now included the trade winds. In the publication that followed the meeting and became a citation classic, Wyrtki wrote: “During a period of strong southeast trades... the circulation in the subtropical gyre is intensified, in particular the South Equatorial Current. This coincides with a buildup of east-west slope of sea level and an accumulation of water in the western Pacific. ... As soon as the wind stress of the southeast

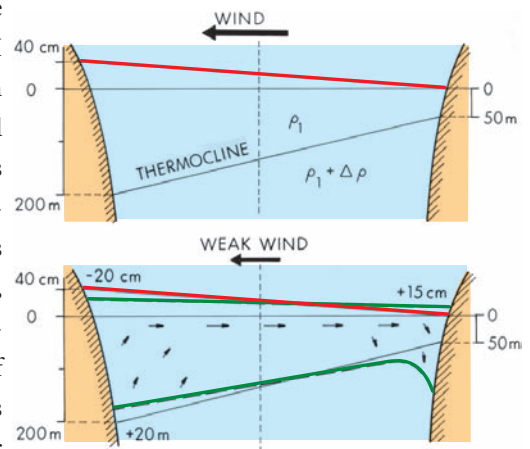


Figure 1: Driven by trade winds, the sea level slopes upward across the Pacific from east to west (red line). During a period of weak winds or westerly winds, sea level falls in the west and rises in the east. With such sea level changes, measured at island stations across the Pacific, Wyrtki documented fluctuations in sea level and thermocline depth (green lines) and in the strength of the tropical current system, from which he then developed his theory of El Niño.



Klaus Wyrтки receives the Alexander Agassiz Medal from Bruce Alberts, President of The National Academy of Sciences. The medal was awarded to Wyrтки in 2004 “for fundamental contributions to the understanding of the oceanic general circulation of abyssal and thermocline waters and for providing the intellectual underpinning for our understanding of ENSO (El Niño).”

trades relaxes, the water accumulated in the western Pacific will tend to move back. This may happen in the form of an internal seiche or internal equatorial Kelvin wave... In any case, it must happen in a mode consistent with the hydrodynamics of the system. It can be assumed that eastward flow in those currents which normally transport water to the east... will be intensified. The result will be an accumulation of warm water in the area off Peru... in essence, El Niño.”⁵

“The first speaker at the Lake Arrowhead meeting was Bjerknes,” Wyrтки recalls. “We had just started to have satellite-observed clouds, and Bjerknes showed the cloud development related to El Niño. The second speaker was Bill Quinn. Quinn said, ‘Whenever the Southern Oscillation reaches a maximum (the southern trade winds are strong) and then weakens, that gives an El Niño. And next year is an El Niño.’ That was the very first El Niño prediction. Then came my talk. I explained

my El Niño theory... the collapse of the wind field, the water rushing east.

“That evening, the three of us decided that we should verify the prediction. There should be an expedition into the waters south of the Galapagos, to see whether the water warms and sea level goes up. I wrote a grant proposal and received funding within a few weeks. We sent our new University of Hawai‘i research ship, the *Moana Wave*, to Peru. Unfortunately, the El Niño was aborted... it came a year later.”

“The year 1975 will not enter oceanographic history as a year of a large El Niño. However, as predicted an El Niño situation started to develop with a characteristic overflow of warm, low salinity water... along the coast,” said the *Science* article that summarized the expedition.

Given this discouraging outcome, Wyrтки awaited anxiously more sea level data from the island tide gauges that covered the 1972–73 El Niño period and the tropical Pacific from the Solomon Islands to the Galapagos. When the data came, he remembers, “Now we will see whether my theory is correct. And there, this figure (he points to a figure of sea level changes in the Solomon Islands and in the Galapagos) shows that before the 1972 El Niño, sea level in Galapagos Island is persistently 5 cm lower than normal; in the west, at the Solomon Islands it is 10 cm above the mean. When El Niño sets in, the water around Solomon Islands drains. Sea level goes down by 30 cm and some time later at Galapagos it goes up. And that is the classical El Niño figure. This verified my theory. Up to that point it was a theory.”⁶

But the theory was shaken by the 82–83 El Niño. Wyrтки: “The story is

that the 1982–1983 El Niño started in a mysterious way. There was a volcanic explosion in Mexico that spoiled all the satellite data world wide. Nobody knew what the real sea surface temperature distribution observed from satellites was. In October 1982, at a Climate Diagnostics Workshop held at the National Center for Atmospheric Research in Boulder, some said, ‘An El Niño is coming,’ and others said, ‘None is coming.’ And I said, ‘None is coming, because I do not see it in the sea level.’ And this became the biggest El Niño of the century!”

“Because at that meeting I claimed there must be a buildup of warm water ahead of El Niño, people said, ‘So this buildup is not necessary.’ But this is not true, it is necessary. The Kelvin wave can only happen when there is a buildup of warm water in the western Pacific.”

Once data became available, Wyrтки documented in several scientific papers what happened to the ocean and the atmosphere during this surprise El Niño. And indeed, the important sea level changes were there. Before El Niño began in June 1982, sea level was about 40 cm higher in the western Pacific than at Galapagos. In January, the sea level across the Pacific was essentially flat. It was the wind that was different from the expected.

In one paper Wyrтки explained, “Previous El Niño events were usually preceded by periods of strong southeast trade winds, which led to a considerable depression of the thermocline in the western equatorial Pacific and to a rise of sea level. Such anomalously strong southeast trade winds did not precede the El Niño of 1982/1983. With the appearance of *westerly winds*

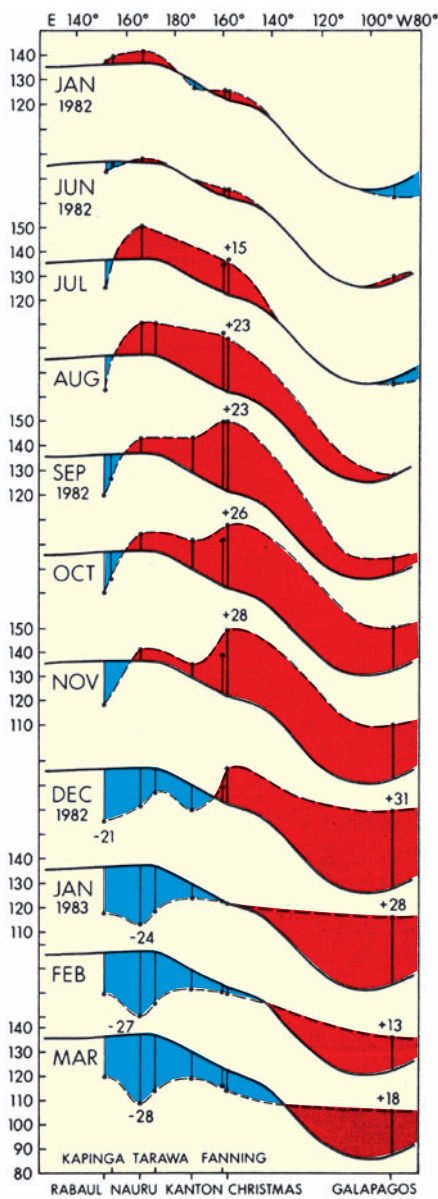


Figure 2: The changes in sea level at the eight stations across the Pacific from January 1982 through March 1983. The Kelvin wave bulge can be seen moving eastward beginning July 1982. By December the sea level across the Pacific is nearly flat. (Adapted from Wyrтки, 1984.)

(italics added) over the western Pacific in July 1982, sea level immediately responded... The generated bulge of water advanced eastward as an equatorial Kelvin wave... As the westerly winds propagated eastward from July through November, sea level in the western Pa-

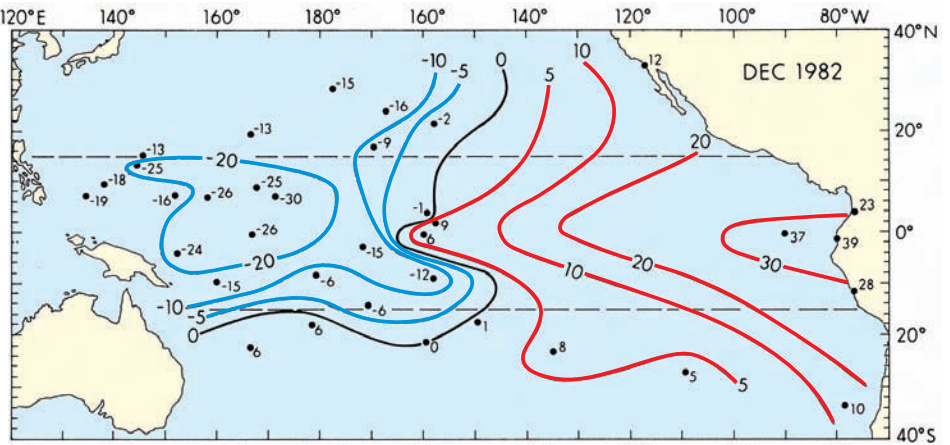


Figure 3: The extent of the Pacific sea level anomalies (in cm) in December 1982. Red contours indicate higher sea level (and warmer water), blue contours lower sea level (and cooler water) than normal. Dots denote sea level stations. (Adapted from Wyrтки, 1985.)

cific decreased... By December 1982 the Kelvin wave had passed Christmas Island, and a peak in sea level of 31 cm had reached the Galapagos Islands.”⁷ The warm water had arrived along the coast of Peru.

Wyrтки took time to adopt the term *equatorial Kelvin wave*. In 1975, he wrote “water flows eastward, probably in an internal equatorial Kelvin wave.” In his 1977 article, he concluded, “The... oceanic response seems to take the form of an equatorial Kelvin wave.” With the analysis of data now from 8 sea level gauges strewn across the Pacific along the equator, he could demonstrate how, in the 82–83 El Niño, “the generated bulge of water advanced eastward as an equatorial Kelvin wave.” (See Figure 2.) He noted, moreover, that “changes in the east-west slope are not limited to the equator. ... The draining of water from the western Pacific affects the area from 20°N to 15°S... The entire equatorial current system is affected and altered.” Asked during the interview about the term equatorial Kelvin wave, Wyrтки says, “That is a mathematical term. I prefer to call it a Kelvin surge because observations

show that the whole equatorial current system is affected.” (See Figure 3.)

In his last years of El Niño research, Wyrтки focused on documenting the evolution of a complete El Niño cycle to answer the question still challenging scientists today: What starts and stops an El Niño? Again, his main tool was sea level measurements.

Numerical models suggested that El Niño events are linked with strong heat transport away from the tropics towards the poles. Using sea level height as an indicator of the volume of water above the thermocline and, therefore, an indicator of heat, Wyrтки showed that over time warm water accumulates in a warm pool on the western Pacific boundary, both north and south of the equator. Periodically, a Kelvin wave “displaces” this warm water to the central and the eastern Pacific, where it then flows poleward along the coasts of North and South America. El Niño is a way for the tropical Pacific to get rid of its heat. “A complete El Niño cycle results in a net heat discharge from the tropical Pacific toward higher latitudes. At the end of the cycle the tropical Pacific is depleted of heat, which can only



Wyrтки on the School of Ocean and Earth Science and Technology research vessel that bears his name.

be restored by the slow accumulation of warm water in the western Pacific by the normal trade winds. Consequently, the time scale of the Southern Oscillation is given by the time required for the accumulation of warm water in the western Pacific. Its release is triggered by fluctuations in the tropical atmosphere.”⁸

Another observation by Wyrтки seems associated with El Niño cycles: “I was intrigued by the fact that the North and South Equatorial Currents vary out of phase. When one is strong, the other is weak. Are the North and South Pacific subtropical gyres also operating out of phase? I was hoping they would be. To measure this asymmetric response, we compared sea level variations in Honolulu and Pago Pago, the only two stations that had sea-level time series good for characterizing changes in the gyre of each hemisphere. The result came out nicely: the gyres alternate, one would be stronger, the other weaker on time scales of four to eight years. I proposed that these oscillations are linked to El Niño.”⁹ I asked

many theoreticians to investigate that problem. Nobody has done so until now.”

In his last scientific talk on El Niño at a TOGA COARE meeting in Noumea, Wyrтки showed how the heat discharge-recharge theory, the out-of-phase relationship between the two subtropical gyres, the fluctuations in the various equatorial currents, the accumulation of water in the warm pool could all be linked with El Niño.¹⁰ “Between two El Niño events the southern gyre accelerates. During these periods the South Equatorial Current is strong, adding warm water to the warm pool, and the Countercurrent is weak, draining less water from the pool. The two effects allow the warm pool to grow. During El Niño, the southern gyre becomes weaker, the Countercurrent stronger, and water drains from the warm pool.” He concluded, “The interaction of the two subtropical gyres is intimately involved in the fluctuations of the warm pool and in the creation of El Niño events.” Critical for this interaction is the Countercurrent, “It is the boundary current between the two subtropical gyres.”

Wyrтки has made many significant contributions to physical oceanography, among them a theory of the thermohaline circulation and a theory of the layer of minimum oxygen. Here only a few highlights have been retold of how Wyrтки has advanced our understanding of El Niño. His students, Roger Lukas, Bill Patzert, Gary Meyers, and William Emery, themselves now all well-known oceanographers, succinctly captured his forty years of contributions to oceanography: “Klaus Wyrтки is an oceanographer in the classical interdisciplinary sense: providing

the grand synthesis whenever possible, making pioneering new observations where data limitations are too great, and approaching his research with an understanding of meteorology and other disciplines.”¹¹

- 1 This “story” was compiled from interviews with Klaus Wyrтки, his written reflections, and excerpts from his publications. I thank Jay McCreary for his clarifications and editing.
- 2 Gunter Dietrich, German Oceanographer
- 3 From Klaus Wyrтки’s “My Scientific Work” written for his children.
- 4 Wyrтки, K., 1973: Teleconnections in the equatorial Pacific Ocean. *Science*, **180**, 262–264
- 5 Wyrтки, K., 1975: El Niño: The dynamic response of the equatorial Pacific Ocean to atmospheric forcing. *JPO*, **5** (4), 572–584, p. 578.
- 6 Wyrтки, K., 1977: Sea level during the 1972 El Niño. *JPO*, **7** (6), 779–787.
- 7 Wyrтки, K., 1984: The slope of sea level along the equator during the 1981/83 El Niño. *JGR*, **89**, 10419–10424.
- 8 Wyrтки, K., 1985: Water displacements and the genesis of El Niño cycles. *JGR*, **90**, 7129–7132.
- 9 Wyrтки, K., and Wenzel, J., 1984: Possible gyre-gyre interaction in the Pacific Ocean. *Nature*, **309**, 538–540.
- 10 Wyrтки, K., 1989: Some thoughts about the West Pacific Warm Pool. In J. Picaut et al. Eds., *Proc. of the Western Pacific International Meeting and Workshop on TOGA COARE*: 99–109.
- 11 Lukas, R., B. Patzert, G. Meyers, and W. Emery: Klaus Wyrтки’s forty years of contributions to oceanography: His students’ perspective. *Oceanography*, April 1990, p. 38.

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Weather Extremes in a Warmer Climate

Extreme weather often leads to disasters. The societal impacts of a warmer climate, thus, depend on how such a climate will affect the nature and frequency of weather extremes. These can be seen as falling loosely into three groups: prolonged extreme conditions such as droughts, heat waves, and cold waves; short-term extremes such as a sequence of rainy days leading to local flooding; and individual brief and violent events such as tornadoes and hurricanes or typhoons that do their damage to a particular place within minutes to a few hours.

In March 2006, NCAR senior scientist **Gerald Meehl**, a member of the IPRC Science Advisory Committee and a JIMAR Visiting Senior Fellow, gave a seminar on weather extremes to scientists at IPRC and the Department of Meteorology, University of Hawai'i. In his talk, Meehl considered aspects of all three kinds of extremes.

Regarding prolonged extreme conditions, Meehl discussed the occurrence of heat waves, defined in two ways. One definition, based on the deadly Chicago 1995 heat wave, is the occurrence of unusually high night-time minimum temperatures for at least three consecutive nights. In projections simulated by versions of the NCAR global coupled atmosphere-ocean general circulation model, Meehl found that the intensity, frequency, and length of heat waves are predicted to increase in the late 21st century in most regions, but most notably in southern and western North America, western Europe, and the Mediterranean.

Meehl also spoke about the occurrence of frost days and the length of growing seasons projected in his atmosphere-ocean GCM. As might be expected, the warmer climate at the end of this century is predicted to have, on average, longer growing seasons (duration of frost-free conditions). The increase in growing season length is far from uniform, however, even for locations at the same latitude. Notably the frost-free season is predicted to increase much more in the U.S. Pacific Northwest than in the Northeast. The change is accompanied by regional patterns of atmospheric pressure trends that promote more warm air advection along the west coast of North America. The predictions concerning the frost-free days are consistent with observations. These show a trend of about 2



Hurricane Katrina, August 28–29, 2005. (Image courtesy of NASA.)

more frost-free days per decade since the 1950s in the Pacific Northwest, while no significant trend has been observed along the U.S. Atlantic coast. Meehl noted that the practical consequences of more frost-free days, and therefore longer growing seasons, are not all positive since the latter may allow harmful pests to proliferate.

All climate models participating in the current assessment of climate change by the Intergovernmental Panel on Climate Change (IPCC) predict an increase in global average precipitation for the warmer climate toward century's end. This increase in precipitation is easily understood as an inevitable consequence of increased evaporation in a warmer world. The models predict more intense precipitation almost everywhere, in both arid and wet regions. At the same time, however, the models generally predict less frequent precipitation events. Thus, on average, the rain in the globally warmed world is predicted to be more intense but also more intermittent than in the present climate.

With respect to violent weather extremes, Meehl remarked on the current surge of interest in global warming effects on tropical cyclone frequency and intensity. He mentioned four recent model studies that deal with this issue. One study, conducted by the Japanese on the Earth Simulator in Yokohama, used a high-resolution (20 km) global GCM. The other three used various kinds of limited-area models. Among the latter, is the study by **Markus Stowasser**, **Yuqing Wang**, and **Kevin Hamilton**, who used the IPRC regional atmospheric model (*IPRC Climate*, Vol. 5, No. 1). The studies agree that in a globally warmed world the total number of tropical cyclones in each major ocean basin may either decrease or not change dramatically but the number of the most intense and destructive storms will increase significantly.

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