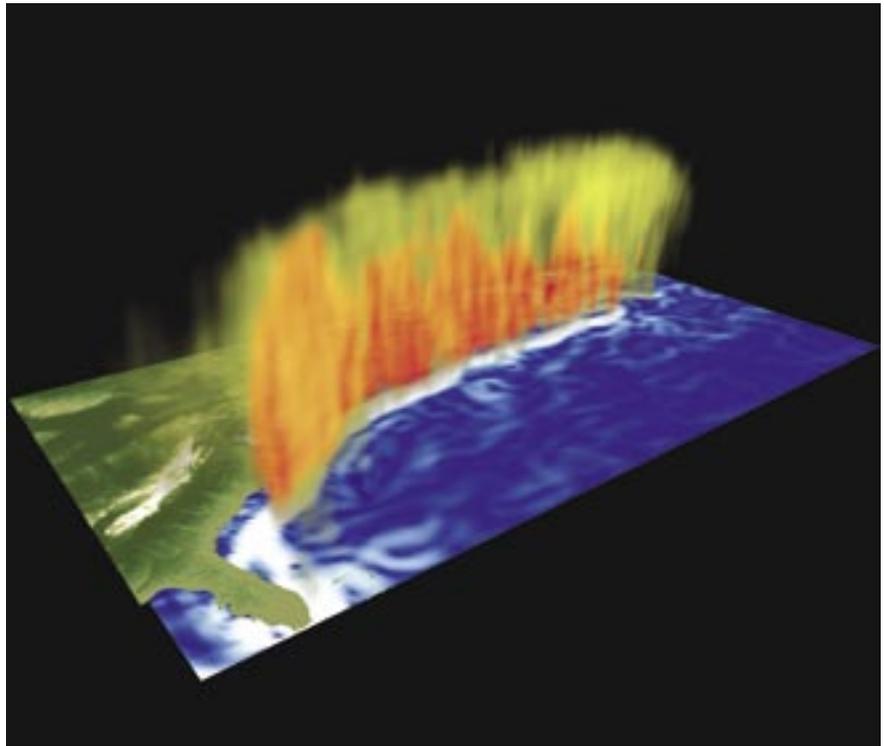


The Gulf Stream's Pathway to Impact Climate



Graphic representation of the Gulf Stream surface current speeds in blue-white (white is the fastest) and upward wind velocities in yellow-red (red for stronger winds), along with land-surface topography of eastern North America. Image, courtesy of Fumiaki Araki and Shintaro Kawahara at JAMSTEC, was made for cover of *Nature* issue.

Ocean surface temperatures and wind speeds tend to vary together across ocean basins away from tropical regions. Typically, stronger surface winds are seen over cooler and weaker winds over warmer water, because strong winds cool the ocean surface by evaporation and by stirring up cold subsurface water. But is this always the case? Aside from warm tropical oceans, where moist air ascends high into the atmosphere, are there instances where the ocean significantly impacts the deep atmosphere? Meteorologists have been skeptical, believing that at midlatitudes, the ocean's effect on the atmosphere is shallow, restricted mainly to the planetary boundary layer.

IPRC scientists and their colleagues at other institutions have been seeking to answer this question by

looking at ocean fronts, where currents bring about sharp gradients in sea-surface temperature. Some of the first support came in 2002 from air soundings over the spectacular meanders, called *Tropical Instability Waves*, along the Pacific equatorial front.¹ The soundings revealed that these meanders affect the whole planetary boundary layer. Next, analyses of satellite data showed stronger winds over the warm flank and weaker winds over the cold flank of the Kuroshio as it flows along the southern coast of Japan.² When the Kuroshio switched between 1998 and 2001 from a straight path that hugs the coast to a meander offshore, the wind fields shifted together with the shift in the Kuroshio path.

Now the results published in the March 13 *Nature* article "Influence of the Gulf Stream on the Troposphere"

show that the signature of this narrow warm current flowing in the cold North Atlantic extends surprising 7 miles high into the upper troposphere.³

The Gulf Stream's impact on climate, keeping Iceland and Scotland comfortable in winter compared to the deep-freeze of Labrador at the same latitude, has been known for a long time. That cyclones tend to spawn over the Gulf Stream is also well known. The study by **Shoshiro Minobe** at Hokkaido University, **Akira Kuwano-Yoshida** and **Nobumasa Komori** at JAMSTEC, and **Shang-Ping Xie** and **Justin Small** at IPRC, now reveals that the Gulf Stream has effects beyond those due to local, low-level atmospheric warming. The rain band that it anchors has strong upward motions that reach as high as the jet stream, where it can excite planetary Rossby waves.

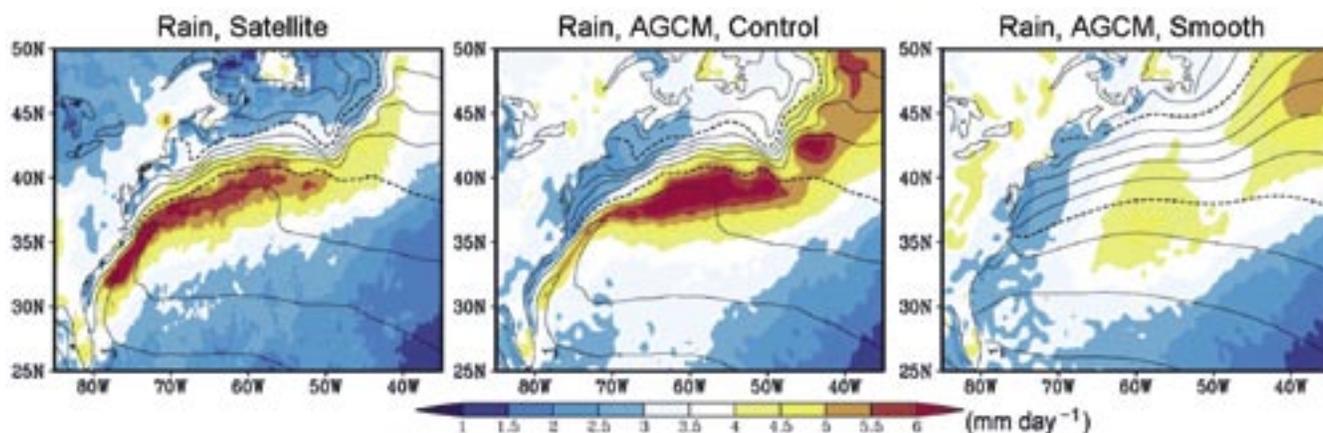


Figure 1. Annual climatology of rain rate: (left) observed by satellites; (middle) in AFES with observed and (right) smoothed SSTs. Contours for SST at 2°C intervals, and dashed contours for 10°C and 20°C (adapted from Minobe et al., 2008, *Nature*, 452, 206–209).

Isolating the climatic influence of the Gulf Stream from energetic weather variations was challenging. Minobe had noticed in high-resolution satellite images the narrow rain band that tends to hover over the warm current. In particular, the narrow rain band hugs the Gulf Stream's warmer flank wherever temperatures rise above 16°C. The winds accelerate and converge over the warm flanks where the rain band is seen. The satellite instruments, however, did not allow measurement of any impact above the marine boundary layer to show the mechanism by which the sea-surface temperature front of the Gulf Stream affects the atmosphere.

The high-resolution European Center for Medium-range Weather Forecast (ECMWF) model analysis provided the data that Minobe needed. The analysis successfully captured the observed downward motion and diverging wind flow on the cold flanks, and the converging winds and rising air over the warm flanks of the current. The analysis, moreover, suggested that the converging winds and rising air resulted from atmospheric pressure differences related to Laplacian sea-level pressure. Previous studies favored the

notion that winds over narrow sea-surface temperature fronts accelerate due to vertical mixing of air. A marine atmospheric boundary layer model simulation of the Gulf Stream region, however, supported the sea-level pressure adjustment mechanism. The upward winds are strongest just above the marine boundary layer, but are still visible at 4 miles, and in the upper troposphere, they diverge right above the Gulf Stream's narrow band.

Experiments conducted by Akira Kuwano-Yoshida and Nobumasa Komori with the high-resolution JAMSTEC Atmospheric General Circulation Model for the Earth Simulator (AFES) provided further evidence that it is indeed the Gulf Stream that caused the rain band and the strong upward wind motion. They first drove AFES with the actual Gulf Stream sharp sea-surface temperature gradient. The model successfully captured the rain band and its signature in the upper troposphere. In the second experiment, they drove the model with smoothed Gulf Stream temperatures; the narrow rain band disappeared (Figure 1).

Analyses of evaporation in the models and in the satellite measure-

ments indicate that evaporation also follows the narrow ribbon of the Gulf Stream, and that this evaporation supplies much of the water vapor that condenses into rain clouds. The ECMWF operational model analysis shows further telltale signs: the converging and diverging winds are more or less in balance; the upward motion of air above the Gulf Stream, however, is much stronger than the downward motion over its cold flanks. The strong upward motion, the authors suggest, reflects the heating released by the condensation of the moist air.

Finally, an analysis of outgoing longwave radiation shows that a high, narrow cloud band hovers slightly to the north of the Gulf Stream ribbon. These high clouds have temperatures frequently below freezing. These observations provide further evidence that the Gulf Stream's influence on the atmosphere reaches far above the lower atmosphere and high enough to excite planetary Rossby waves disturbing the atmosphere.

The findings take on even more significance when considering the fact that the Gulf Stream is the upper branch of the Atlantic portion of the ocean

conveyor belt that drives the global ocean circulation. The conveyor belt is predicted to slow down with global warming. During times that Earth's climate switched between ice ages and warm periods, the Gulf Stream's strength changed markedly. Closely linked to these changes have been climate changes not only in the Atlantic, but also in the Pacific and even in the Southern Hemisphere. Scientists have suspected that in addition to the Gulf Stream's role in ocean circulation, there is an atmospheric bridge that conveys climate signals emitted from the Gulf Stream to other regions in the Northern Hemisphere.

Thus, the narrow Gulf Stream creates a vertical pathway—the deep heating of the atmosphere—by which it can impact large-scale climate (Figure 2). The heating can generate planetary waves that alter climate over Europe and beyond by riding on the westerly jet stream in the upper troposphere.

REFLECTIONS

The Gulf Stream article created a stir. Newspapers around the world picked up the press releases, and the authors were interviewed by reporters in Japan, United States, United Kingdom, and other European countries. The study was described in such popular-scientific magazines as the *Scientific American* and the *Geotimes*. The editors of the *IPRC Climate* thought, therefore, that our readers might like to find out how this article came about, and we asked the authors to send us their reflections.

Shoshiro Minobe: I begin this reflection with saying that Shang-Ping Xie and I were colleagues at Hokkaido University during the latter part of the 90's. Stimulated by a series of Xie-san's papers using QuikSCAT and TRMM,^{1,2,4,5} I started sometime in 2005 to analyze satellite precipitation data. Before then, I had looked neither at precipitation nor surface wind satellite data. Soon I noticed the precipitation band over the Gulf Stream and that the surface wind convergence could not be explained by vertical mixing, a popular hypothesis others have used to explain wind patterns near sharp ocean fronts. I suspected that pressure adjustments may be the responsible mechanism, and in order to test this idea and to determine which signatures in other physical parameters related to the phenomenon, I requested the high-resolution ECMWF operational analysis in early 2006. Also, roughly at the same time, I invited Komori-san at the Atmosphere and

Ocean Simulation Research Group of the Earth Simulator Center to collaborate with me on simulation of ocean-to-atmosphere feedback over the Gulf Stream using the Atmospheric General Circulation Model for the Earth Simulator (AFES).

The collaboration with Xie-san began, when for the Spring 2006 meeting of the Meteorological Society of Japan in Tsukuba, I submitted an abstract of my results on the satellite observations, and Xie-san, who was the convener at that meeting of the special session "Coupled ocean-atmospheric phenomena in the Indo-Pacific region," noticed the abstract and contacted me. I was actually impressed by the fact that he grasped the potential importance of our study from the one-page abstract. Fortunately, I happened to travel on business to Hawai'i before the meeting and was able to visit the IPRC for one day in April 2006. Xie-san and I met, and we discussed the findings and what kind of experiments would be most effective with AFES. Just before my visit to the IPRC, I found the important results from the ECMWF operational analysis that showed the surface wind convergences are closely related to

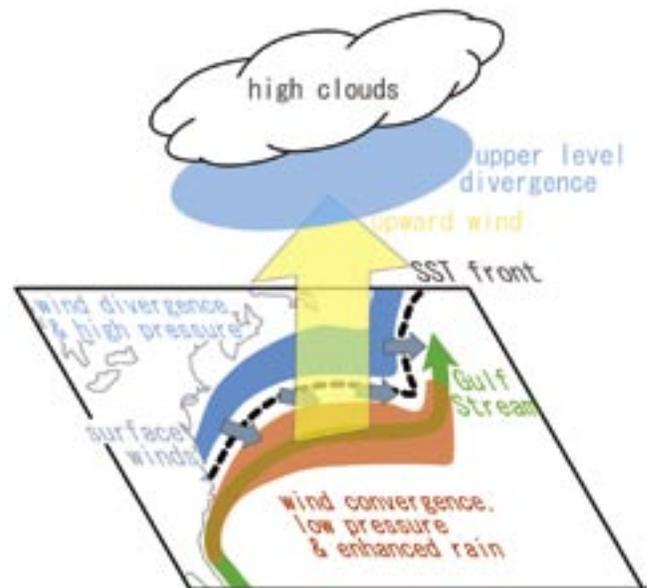
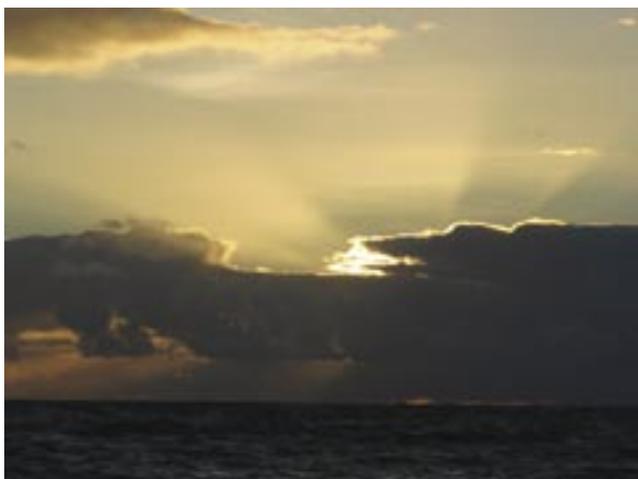


Figure 2. A schematic of the climatic responses to the Gulf Stream. The warm Gulf Stream (green arrow) creates a sharp sea-surface temperature front (black dashed line) in the cold Atlantic. The surface winds flow toward the warm Gulf Stream (gray arrows) and the warm air rises (yellow arrow), creating a region of rain (orange band). The upward motion over the Gulf Stream penetrates into the upper troposphere, creating high clouds. In the upper troposphere, the winds branch out (blue oval), forming planetary waves that travel eastward toward Europe (adapted from Minobe et al. 2008; *Nature*, vol. 452).

Laplacian sea-level pressures. Also, the upward winds occur roughly over the Gulf Stream in the ECMWF analysis; they are prominent at 500 hPa and discernible even at 300 hPa. This is quite exciting; the aforementioned vertical mixing process mainly occurs in the surface layer, which is usually assumed to occupy the lower one-tenth of the atmospheric boundary layer or the lowest 100 m. The deep penetration of the upward winds and associated horizontal wind divergence in the upper troposphere indicate that the direct influence of the Gulf Stream penetrates about 100 times higher than that expected from vertical mixing alone.

At the May meeting in Tsukuba, Xie-san, Komori-san, Yoshida-san and I discussed and agreed upon the conditions for the AFES experiments. The experiments were to demonstrate that the precipitations and warm rising air were effects of the narrow Gulf Stream sea-surface temperature gradient. Komori-san and Yoshida-san ran the experiments on the Earth Simulator, completing them by August. About the same time (September 2006), I found the outgoing longwave radiation signature along the Gulf Stream that documented the high altitude of the clouds. So, we essentially obtained the results presented in *Nature* within about one year or so.

The writing took a little longer than I expected. My one week visit to the IPRC in February 2007 was helpful. Without Xie-san's broad knowledge and insightful comments, we would probably not have made it into *Nature*. My next visit to the IPRC in August 2007 was also fruitful, particularly the talks with Justin Small, who examined the linear response of the atmosphere to heating above the Gulf Stream. His results indicate that the atmospheric heating due to the Gulf Stream can generate atmospheric Rossby waves with sizable amplitudes. All in all, I think that the process from inception to publication was amazingly fast.



Akira Kuwano-Yoshida and Nobumasa Komori: We, Akira and Nobu, are immigrants from Earth to the virtual earth called “CFES” (Coupled General Circulation Model for the Earth Simulator). Since this virtual planet was unexplored, we grew forests, dug ground, opened straits, and made clouds to mimic our mother planet. Sometimes, we go back to Earth and report on the current status of CFES. A first encounter with Minobe-san from Earth was at the 2005 Spring Meeting of the Meteorological Society of Japan (MSJ) in Tokyo, when Nobu showed some pictures taken of our virtual planet. The pictures included a precipitation band over the Kuroshio extension front. Minobe-san asked the virtual oceanographer, “How tall is the signal?” He again asked the same question at the 2005 IAG/IAPSO/IABO Joint Assembly in Cairns, Australia, but Nobu did not have any idea yet. Finally, Minobe-san came all the way to our virtual earth in Yokohama on 14 February 2006 (St. Valentine’s Day) and Akira, a virtual meteorologist, joined the discussion as a translator between the Earth climatologist and the virtual oceanographer. Using satellite observations of Earth, Minobe-san had found that precipitation is anchored by sea-surface temperature (SST) gradients, such as along the Gulf Stream. He had already figured out the cause, pressure adjustment mechanism. Although we had noticed a similar feature in CFES, we did not have enough time and knowledge to determine its causes. We were so busy breaking in CFES. By coincidence, it was just one month before Bunmei, which means “civilization” in Japanese, emigrated to our barren planet from an island of perpetual summer, where Xie-san lives.

At the 2006 Spring Meeting of the MSJ in Tsukuba, Minobe-san and Xie-san suggested the experiment using AFES, the atmosphere of CFES. When we fed the down-on-earth SST from satellite observations to AFES, we saw a similar concentration of rain over the Gulf Stream as the satellite pictures show. The rain band disappeared when we fed AFES with artificial smoothed SST! Furthermore, we found that extratropical cyclone activity was also anchored by the Gulf Stream and disappeared in the smoothed SST run. We sent only a small part of the experiment data, about 400 GB, to Minobe-san in September 2006. Using outgoing longwave radiation data from our virtual earth, he found in just 10 days that high clouds occurred frequently over the Gulf Stream. He verified this with satellite observations of Earth. It was amazing for us: our virtual earth was able to capture Earth’s real behavior that had been unknown to humans.



The authors from left, Shoshiro Minobe, Justin Small, Shang-Ping Xie, Akira Kuwano-Yoshida, and Nobumasa Komori.

After that, all we could do was to follow tempestuous discussions between the Earth men, Minobe-san and Xie-san, and *Nature*. A large number of emails with energetic discussions passed in front of us. We, of course, continued to explore our planet and looked into whether cyclone activity varied with seasons. Akira presented the results at IUGG in Italy in July 2007. At the end of November 2007, fortunately, the paper received quite positive evaluation from the editor of *Nature*. We were happy, because *Nature* recognized that our virtual earth was comparable to “nature”, and “pacific” days came back to our life.

But not for long! It was 11 December 2007, when Minobe-san brought up the idea of making a cover for *Nature*. Xie-san knew that visualization researchers also live on our virtual planet and suggested we get their help. They study how the virtual earth, consisting of only digits, can be seen by human eyes. We asked some of them, Fumiaki and Shintaro, to make a 3D picture from the ECMWF data within a week. They agreed readily, making beautiful pictures, and one of them was chosen as the cover of *Nature*!

The *Nature* paper is the start, not the goal for us in the exploration of our virtual CFES earth, though the days of success were precious for us young virtual earth researchers.

Shang-Ping Xie: In 2003, the Ocean-Atmosphere Group at the Earth Simulator Center, in collaboration with the Frontier Research Center for Global Change (FRCGC), began producing results from their high-resolution simulations. During that summer, Youichi Tanimoto invited me to visit Hokkaido University. He and Shozo Yamane, then at FRCGC, made available the output from the high-resolution AFES simulations. In browsing the AFES output in Sapporo, I noticed that the Gulf Stream anchors a narrow rain band

that meanders with the warm current, a collocation I confirmed with microwave satellite observations. That was interesting but still needed additional results to be a substantial paper. Subsequent reading of the literature made me aware of observations hinting at strong climatic effects of the Gulf Stream: stratocumulus clouds often begin to develop strongly on the warm flank of this warm current during winter cold surges;

coastal weather radars, with a limited offshore range, suggested high echo tops over the Gulf Stream; most interestingly, satellites record high occurrence of lightning over the Gulf Stream, indicative of tall and cold clouds there. All these observations went into our *Nature* paper as circumstantial evidence for robust and deep atmospheric effects of the Gulf Stream.

On his visit to IPRC in 2005, Tatsushi Tokioka, the director general of FRCGC, suggested holding a joint session at a semiannual meeting of the Meteorological Society of Japan (MSJ). As a result, Hisashi Nakamura of FRCGC and The University of Tokyo and I convened a special session on Indo-Pacific climate variability at the 2006 Spring Meeting of the MSJ in Tsukuba. Two months before the meeting, Shoshiro Minobe submitted an abstract on the Gulf Stream’s climatic effects; the abstract struck a chord with me. I immediately e-mailed Shoshiro and the rest is detailed in his reflections. I have known Shoshiro for 20 years, but this is the first time we collaborated on a paper. Shoshiro’s drive, initiative, leadership, and perseverance made it possible for our paper to appear in *Nature* and on its cover. His idea to relate sea-level pressure Laplacian to surface wind divergence is ingenious, and his enthusiasm affected and drove us all involved.



As often happens, the success of this project owes much to those who are not on the author list. Some of their names appear above. They enlightened us and afforded opportunities for us to connect and go beyond what we can do by ourselves.

The paper travelled with us far beyond Japan and Hawai'i as we worked on it. I received a version of the manuscript last summer while visiting the Ocean University of China in Qingdao. I locked myself up and worked on the paper. Another time, on a very early morning after getting off a red-eye cross-Atlantic flight, I was in the lobby of an Amsterdam hotel waiting for my room to be ready, when I received the first decision from *Nature*, which Shoshiro had forwarded to me. I was thrilled that two reviews were very positive, but the third had concerns. Shoshiro and I then exchanged many e-mails and phone calls to discuss the revision. We were very pleased that eventually all three reviewers enthusiastically supported our paper in *Nature*.

Justin Small: I had been working at IPRC on how the atmosphere re-

sponds to Tropical Instability Waves, in collaboration with Shang-Ping Xie and Yuqing Wang. I was naturally curious to see if similar effects occurred over mid-latitude fronts. Therefore I was glad to be introduced to the work of Minobe and Xie on the Gulf Stream at an early stage. Looking at the estimates of “diabatic heating” in the atmosphere (mostly caused by condensation of water vapor during convection) from the Tropical Rainfall Measuring Mission satellite, I noticed that convection over the Gulf Stream occurred deep in the atmosphere. However, the accuracy of these new estimates was not clear, and so the independent results of Minobe-san helped me in interpreting the satellite data.

I extended this analysis by running model simulations of the planetary wave response to the deep diabatic heating over the Gulf Stream. I was very pleased that Minobe-san and Xie were interested in this research, and they asked me to be a co-author, which I gladly accepted. It was a fascinating and enjoyable way to bring my research at IPRC to a close.



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