Microwave SST Observations of Transequatorial Tropical Instability Waves

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Abstract

Satellite microwave measurements of sea-surface temperature (SST) reveal previously unreported features of tropical instability waves (TIWs). In the Pacific, TIW-related variability is observed from the eastern boundary to at least 160°E. Cusp-shaped distortions of SST fronts and associated trains of anticyclonic vortices propagate westward both north and south of the equator with approximately 50% larger displacements in the north. In the Atlantic, TIWs and associated anticyclonic vortices are clearly observed only on the north side of the equator where they propagate from the eastern boundary to the western boundary.

Introduction

Early satellite observations of sea-surface temperature (SST) in the Pacific [*Legeckis,* 1977; *Legeckis et al.,* 1983] and Atlantic [*Legeckis and Reverdin,* 1987] exposed the existence of westward-propagating waves a few degrees north of the equator with wavelengths, periods and phase speeds of about 1000 km, 21 days and $0.5\,\mathrm{m\,s^{-1}}$ [*Qiao and Weisberg,* 1995]. Models and observations conclude that these waves are generated by instabilities of the equatorial currents [e.g., *Luther et al.*, 1990; *Masina et al.*, 1999]. The waves are thus referred to as tropical instability waves (TIWs).

A diagnostic feature of instability analyses of equatorial currents is that the fastest-growing waves should be transequatorially coherent with larger amplitude north of the equator and approximately symmetric phase of meridional velocity perturbations [e.g., *Yu et al.* 1995]. This implies approximately antisymmetric pressure perturbations. To the extent that velocity streamlines coincide with isotherms, SST perturbations should also have equatorially antisymmetric phase structure.

The predicted southern signatures of TIWs have not yet been reported from SST. This is perhaps due to limited data coverage because the tropics are cloud covered about 60% of the time [*Hahn et al.,* 1995], thus obscuring SST from the infrared sensors that have been available for satellite measurements of SST. Here we investigate the evolution of TIWs from satellite microwave observations which are capable of measuring SST in nearly all weather conditions.

The Evolution of TIWs

Since December 1997, the TRMM (Tropical Rainfall Measuring Mission) Microwave Imager (TMI) has been observing the Earth over the 10.7-85.0 GHz range of the microwave spectrum [*Kummerow et al.,* 1998]. The atmosphere is nearly transparent at the lower frequencies, thereby allowing measurements of SST under all weather conditions excluding rain. Rain-contaminated observations are easily identified [*Wentz and Spencer,* 1998]. A physically based algorithm is used to estimate SST at a spatial resolution of 46 km with an rms accuracy of 0.5°C [*Wentz,* 1998].

For present purposes, the SST measurements have been composite averaged over 3-day periods. TMI coverage exceeds 90% throughout most of the tropics while infrared coverage by the Advanced Very High Resolution Radiometer (AVHRR) is less than 60% over vast regions (Figure 1).

Figure 1

The TMI data clearly show the synoptic temporal evolution of TIWs.[1] Consistent with previous satellite and in situ observations [*Legeckis et al.,* 1983; *Baturin et al.,* 1997], TIWs were absent during the 1997-98 El Niño. Cold water first appeared along the equator east of 140°W on 13 May 1998, signaling the demise of El Niño conditions. Within a week, an equatorial cold tongue extended west to the dateline and cusp-shaped wave patterns appeared almost immediately along its northern flank.

The upper four panels on the cover show maps of SST at 10-day intervals during the early stages of the 1998-99 TIW season. In the June 12 map, two large cusps that formed near the Galapagos during the last week of May had propagated west to 112°W and 103°W. In the succeeding maps, these cusps continued to propagate west while smaller cusps farther west grew and new cusps formed to the east.

The most interesting features of the SST field are the similar cusp patterns along the southern flank of the Pacific cold tongue. Although less well defined during the early stages of development, the southern hemisphere cusps grew and propagated westward like their northern hemisphere counterparts.

Also evident are swirls of cold water rotating clockwise off the northern cusps, indicative of anticyclonic vortices between the cusps. A survey of one such vortex during 1990 found that the feature extended to a depth of 150 m with a diameter of about 500 km [*Flament et al.,* 1996]. The southern hemisphere cusps are usually tipped backward, suggestive of anticyclonic (counterclockwise-rotating) vortices there as well.

A similar progression of SST occurred somewhat earlier in the Atlantic. Westward-propagating cusps developed along 1°N almost immediately after the appearance of equatorial cold water on 26 April 1998. A pair of cusps near 18°W and 26°W in the June 12 map grew and propagated west in the succeeding maps while new cusps formed farther east. As in the Pacific, the cusps were associated with anticyclonic vortices. Unlike the Pacific, however, there was no clear evidence of TIW-induced SST perturbations south of the equator.

The SST fronts remained well defined in the Pacific until February 1999. In the October-November 1998 panels on the cover, TIWs were highly developed with wavetrains of cusps and associated vortices on both

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[1] An animation of Pacific and Atlantic TIWs can be viewed from the TRMM Data page of http://www.remss.com/.

sides of the equator as far west as 160°E. The wavetrains on opposite sides of the equator propagated west with visually indistinguishable phase speeds. The cross-equatorial alignments of cusps are difficult to quantify since the cusps become progressively distorted with increasing distance from the equator.

In the Atlantic, the SST gradient never intensified south of the equator and the northern SST front weakened in August 1998. Thereafter, SST signatures of TIWs became more difficult to detect. A large cusp and its associated vortex impinging on the Brazilian coast are nonetheless apparent in the 26 October 1998 map and at other times during the TMI data record.

Limitations of SST Detection of TIWs

In the above description, the existence of meridional gradients of average SST ($d\overline{T}/dy$) are crucial to the detection of TIWs. In the Pacific, the strong positive and negative $d\overline{T}/dy$ are associated with the SST fronts that bracket the equatorial cold tongue (Figure 2). East of 100°W, the southern front disappears and the northern front shifts southward, crossing the equator at 90°W. In the Atlantic, there was only a northern front. SST gradients were too weak in the Indian Ocean to detect TIWs, if they existed there.

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SST variability associated with TIWs can be isolated by high-pass filtering to remove variability with time scales longer than 50 days. Areas of large-amplitude variability coincided with areas of large poleward $d\overline{T}/dy$ (Figure 2). Note in particular that the northern band of high SST variability in the Pacific crossed the equator following the northern SST front all the way to the eastern boundary.

West of 110°W, the amplitudes of Pacific SST variations for a given $\left|d\overline{T}/dy\right|$ were larger in the northern hemisphere (Figure 3). For a poleward $d\overline{T}/dy$ of 1°C per 100 km, for example, SST standard deviations were about 1°C north of the equator but only 0.75°C south of the equator. SST perturbations north of the equator were smaller in the Atlantic and SST variability was below the noise level south of the equator.

3

The slopes of straight-line fits to the scatter plots in Figure 3 are a measure of the TIW-induced meridional displacement of isotherms. Results obtained for the North Pacific, South Pacific and North Atlantic are 80, 55 and 50 km, respectively. For sinusoidally meandering isotherms, these correspond to peak-to-peak meridional displacements of 226, 156 and 141 km. Because of the highly nonlinear cusped nature and nonstationarity of the amplitudes of TIWs, displacements can be twice as large (see cover). The ratio of about 1.5 between northern and southern displacements in the Pacific is consistent with the larger northern amplitudes of TIWs predicted from instability theories.

SST variability when $d\overline{T}/dy = 0$ represents measurement noise plus signals unrelated to TIWs. The zero intercepts of about 0.5°C in Figure 3 are thus an upper-bound estimate of the imprecision of 3-day composite average SST. This is consistent with the 0.5°C accuracy estimate for individual TMI measurements of SST [*Wentz,* 1998].

Discussion

The microwave measurements of SST presented here reveal previously unreported features of TIWs: SST signatures of TIWs are evident on *both* sides of the equator in the Pacific with about 50% larger amplitude in the north; the northern band of short-period Pacific SST variability indicates that TIW signals extend east of 100°W to the eastern boundary; Pacific TIWs propagate farther west than the dateline, perhaps all the way to the western boundary, although this cannot be determined from SST since $d\overline{T}/dy$ becomes very weak west of 160°E.

Flament et al. [1986] suggested that the cusp-shaped distortions of the northern SST front are caused by anticyclonic vortices. The prevalence of cusps in the TMI data suggests that these vortices are very common on both sides of the equator in the Pacific and north of the equator in the Atlantic. Moreover, the vortices apparently form in very regular trains.

The availability of TMI data in nearly all weather conditions allows an uninterrupted record of the propagation of SST signatures of TIWs. From a time-longitude section along 2°N in the Pacific (Figure 4), westward propagation became apparent west of 100°W beginning in late May 1998, coincident with the onset of a strong $d\overline{T}/dy$ after the collapse of the 1997-98 El Niño. In late February 1999, westward propagation appears to have terminated west of 110°W and begun again near the eastern boundary. A phase speed of 0.53 m s^{-1} was estimated by the Radon transform method [*Deans,* 1993] applied to the period June 1998-February 1999.

Figure 4

Westward propagation is also evident along 2°S where small amplitude TIWs appeared in May 1998 at the same time that TIWs appeared along 2°N (Figure 4). For reasons yet to be determined, the amplitudes of the southern SST perturbations increased considerably in late August 1998 and persisted west of 110°W for about a month longer than the northern TIWs. The phase speed estimate along 2°S was 0.50 m s^{-1}, very similar to the phase speed estimate along 2°N.

Although the ∼0.5 m s^{-1} signals are dominant, much faster westward propagating signals with longer wavelengths and smaller amplitudes are clearly seen superposed in both panels of Figure 4. TIWs are thus associated with two wave-like signals with distinctly different wavenumber and frequency characteristics. The nature of these waves is under investigation.

The close association between $d\overline{T}/dy$ and the amplitudes of SST perturbations is not surprising. Wave-induced lateral movements of isotherms result in large SST variations at a fixed latitude when $d\overline{T}/dy$ is large. Furthermore, the strength of $d\overline{T}/dy$, as it reflects the mean zonal current structure, is itself an index of the times and locations of the potential for lateral shear instabilities that would generate TIWs. It is possible that TIWs exist when and where $d\overline{T}/dy$ is weak but cannot be detected because the associated SST variations fall below the noise level. This could be investigated from measurements of dynamical variables such as meridional velocity or sea level.

As a case in point and consistent with previous studies, there was no evidence of propagation east of 100°W along 2°N during the 1998-99 TIW season. As noted above, the northern front and associated band of SST variability were south of 2°N at these longitudes (Figure 2). The isolated band of SST variations along 2°S (Figure 4) over the longitude range where the northern front extends from 90°W to the eastern boundary indicates that TIW-induced SST variability existed along the entire northern front. After February 1999, TIW-induced SST variability was evident near the eastern boundary along 2°N where TIWs became detectable because the northern front had shifted to the north.

Time-longitude sections in the Atlantic (not shown here) are similar to the Pacific sections. SST perturbations were apparent on both sides of the equator, but with barely detectable magnitudes and intermittent occurrence along 1°S. The estimated phase speed along 1°N was 0.31 m s^{-1}, much slower than in the Pacific.

The South Pacific signatures of TIWs identified from TMI data are key features that provide insight into the dynamics of the waves. The difficulty identifying systematic cross-equatorial alignment of the cusps suggests complicated and perhaps variable phase structure. This is in marked contrast to the simple symmetric cross-equatorial phase structure inferred from sea level measured by the TOPEX/POSEIDON satellite altimeter [*Chelton et al.*, 1999, The latitudinal structure of monthly variability in the tropical Pacific, manuscript submitted to *J. Phys. Oceanogr.*]. An effort to reconcile this apparent contradiction is the subject of ongoing research.

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