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A decadal spiciness mode in the tropics

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Abstract. Analysis of a complex climate model suggests the existence of a mode of coupled ocean- atmosphere variability in the tropical Pacific with the following dynamics. Anomalous strong Pacific trade winds accelerate the North Equatorial current and Countercurrent. At 10° to 15°N in the central Pacific thermocline this causes anomalous advection across mean gradients of temperature and salinity on isopycnal surfaces and generates cool/fresh spiciness anomalies of the order of 0.3°K. These are advected by the mean circulation via the western boundary region to the equatorial Pacific in approximately five years. At the equatorial outcrops of the isopycnals, the cool/fresh anomalies affect the surface heat budget and are hypothesized to initiate a relaxation of the trade winds that is reinforced by positive feedbacks with the slope of the thermocline and with air-sea fluxes of heat and freshwater. At 5° to 10°S the decrease of the trades generates by anomalous advection cool/fresh spiciness anomalies that migrate to the equator in one to two years and provide a positive feedback. At 10° to 15°N, the decrease of the trades decelerates North Equatorial current and Countercurrent and causes warm/salty anomalies on isopycnals that arrive at the equator five years later and close the cycle.

Introduction

Thermal anomalies sequestered in the upper ocean provide the memory of the climate system and their propagation and emergence at the surface is hypothesized to determine the time-scale of decadal climate variability (Latif and Barnett 1994, 1996, Gu and Philander 1997). The evolution of these low-frequency thermal anomalies is governed by two distinct dynamics (Schneider et al. 1999). Thermal perturbations that affect the oceanic density are governed by planetary wave dynamics (Huang and Pedlosky 1999, Liu 1999) while perturbations that are density compensated by anomalies of salinity evolve like a passive tracer. The latter are referred to as anomalies of ocean spiciness (Munk 1981), a variable that describes how hot and salty ('spicy') water of a given density is. Here, a decadal climate mode is presented that stems from advection of spiciness anomalies on isopycnal surfaces from the tropical Pacific to the equatorial region.

The coupled model

A 130 year integration of a global, ocean-atmosphere general circulation model (Frey et al. 1997) was analyzed. Its full primitive-equation ocean module has 20 levels in the vertical, and has a resolution of 2.8° longitude and 0.5° latitude within 20° of the equator. Further poleward, the meridional resolution decreases smoothly to 2.8°. The atmosphere is run at a spectral truncation of T42 and employs a suite of subgrid scale parameterizations. The ocean and atmosphere exchange fluxes of heat, fresh water and momentum without any flux correction within 60° latitude of the equator. Poleward, surface temperature and salinity are relaxed to climatology.

The simulation produced overall a realistic mean state, seasonal cycle and interannual variability (Frey et al. 1997, Pierce et al. 1999). Problems of significance for the dynamics discussed here include an equatorial cold tongue that extends too far to the west, a feature common in coupled models; an Indonesian throughflow predominately composed of southern, rather than the observed northern (Ilahude and Gordon 1996) hemisphere waters; and an overly pronounced temperature-salinity front separating subtropical salty and warm and tropical cool and fresh waters on shallow isopycnals in the northern hemisphere Pacific.

Spiciness anomalies

To distinguish dynamics of planetary waves from advection along isopycnal surfaces, modeled ocean temperature and salinity are converted to depth of density surfaces (isopycnals), and to temperature on isopycnals, a measure for spiciness. This reveals large variance of temperature on isopycnals in the tropical western Pacific with a time scale of ten years and a magnitude of 0.4°K (Figure 1). The leading complex empirical orthogonal function (CEOF, Barnett 1983) of the temperature anomalies between the 24.0 and 24.5 kg m^{-3} σ_Θ isopycnals captures this decadal signal and allows a reconstruction of a typical cycle of this climate mode.

In the northern hemisphere, cool/fresh spiciness anomalies (Figure 2) appear close to the surface east of the date line between 10-15°N (year 0) and intensify to 0.3°C while propagating westward towards the coast of Asia (year 1 to 2) along isopycnal surfaces that increases their depth to 150 m (Figure 3) and are detached from the direct influence of air-sea fluxes of heat and fresh water. Once at the western boundary (year 4), anomalies spread to the low latitudes and fill the western tropical Pacific north of the equator with anomalous cool and fresh water (years 5 to 7).

The arrival of northern anomalies in the equatorial region (year 0 and 1) is marked by the initiation of anomalies of opposite sign at 10-15°N east of the date line and of like sign at 10-15°S. The southern hemispheric warm/salty spiciness anomalies propagate to the equator (Figure 3) and in years 2 and 3 reinforce warm/salty anomalies just north of the equator, at a time when the cool anomalies at 10-15° of latitude reach largest values.

Associated atmospheric fluxes and ocean currents

During year 2 of the cycle the associated pattern of atmospheric fluxes reach largest values in a standing oscillation

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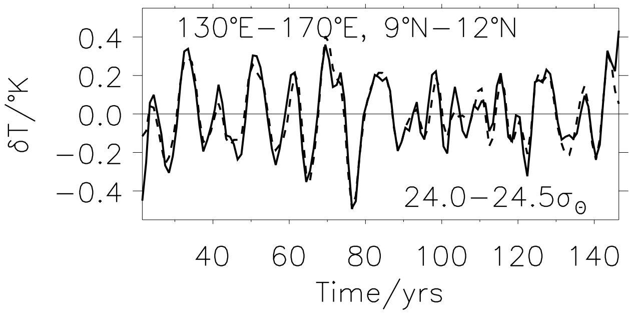

Figure 1. Evolution of spiciness in the western tropical Pacific as measured by temperature anomalies in °K on an isopycnal. The thick line shows anomalies between of the 24.0 and 24.5 kg m^{-3} σ_Θ isopycnals that are typical for the spiciness anomalies of the 22.0 to 26.0 kg m^{-3} σ_Θ surfaces. The reconstruction of the 24.0 to 24.5 kg m^{-3} σ_Θ spiciness anomalies from their leading complex empirical orthogonal function (CEOF) is shown by a dashed line and explains over 90% of the local variance. All results have been band passed to allow variability with periods of 3 to 20 years only. Note the ten year time scale of spiciness on all isopycnals that is well represented by the leading CEOF.

that marks a shift of atmospheric centers of deep convection from the equatorial western and south Pacific to 10°N (Figure 4). This shift is associated (Gill 1980) with changes of the wind stress curl that accelerate and shift northward the border between the North Equatorial Countercurrent and North Equatorial Current (Figure 5). In the southern hemisphere, the south equatorial current at 10°S accelerates at the expense of the (weak) Southern Countercurrent. These changes of the currents and winds are in approximate Sverdrup balance with a one to two year lag. Planetary waves propagation can therefore not explain the ten year time scale of the oscillation.

The anomalies of the geostrophic currents during years 2 and 3 are accompanied by an increase in the speed of the shallow equatorial circulation (McCreary and Lu 1994) that consists of Ekman transports at the surface, geostrophic return flow below and equatorial upwelling.

Generation of spiciness anomalies

The anomalous currents displace a temperature front on the isopycnals that extends across the Pacific from 16°N in the east to 10°N in the west and separates salty and warm waters subducted in the central subtropical and tropical Pacific from fresh and cool water in the shadow region to the south (Figure 5). This anomalous advection across mean spiciness gradient, rather than surface fluxes of heat or fresh water, cause the subsurface growth of the temperature and salinity anomalies on the isopycnal (Figure 2). Once generated, the spiciness anomalies are advected by the mean circulation via the western boundary currents to the equatorial region (Figure 3). The advection time is five years and sets the ten year period of the mode.

In the southern hemisphere, the acceleration of the south equatorial current (Figure 5) displaces the warm and salty waters westward, and generates positive spiciness anomalies that are advected with the mean circulation along a direct, mid–oceanic path to the equator (Figure 3). This accounts for the fast transit of the southern hemisphere anomalies.

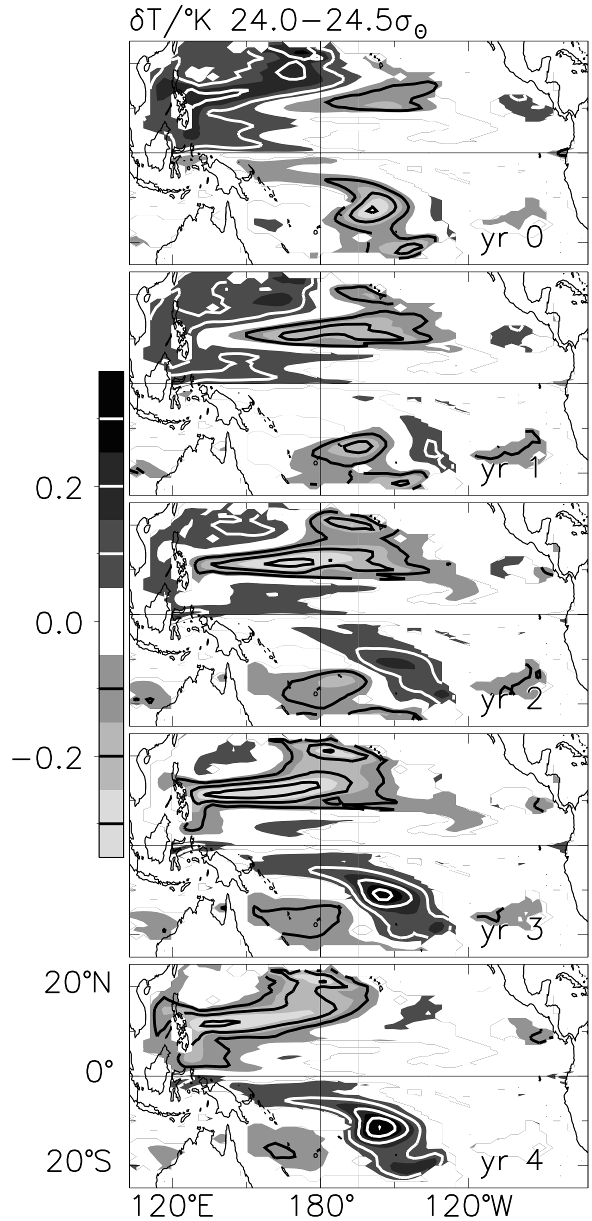

Figure 2. Reconstruction of the evolution of the spiciness mode during one half cycle as measured by temperature in the layer bounded by the 24.0 and 24.5 kg m^{-3} σ_Θ isopycnals. Contour interval is .1°K and gray scale is given on left. The panels correspond to successive years (indicated in lower right corner), and the second half of the 10 year cycle is obtained by adding 5 years to the year counter and reversing the sign of anomalies. The reconstruction is obtained from the leading CEOF of the spiciness anomalies by multiplication of the spatial loading pattern with a constant, representative amplitude and linearly advancing phase corresponding to a typical period of 10 years. The leading CEOF explains 33% of the variance of the band passed filtered data in a 3 to 20 year period spectral window. Fitting an AR-1 process to this principle component yields a period of 9.9 years and a decay time of 24 years. Results are only contoured for those points where the CEOF explains more than 10% of the local variance.

Equatorial emergence and feedback hypothesis

Once in the equatorial region, the warm spiciness anomalies are advected eastward in the equatorial undercurrent and

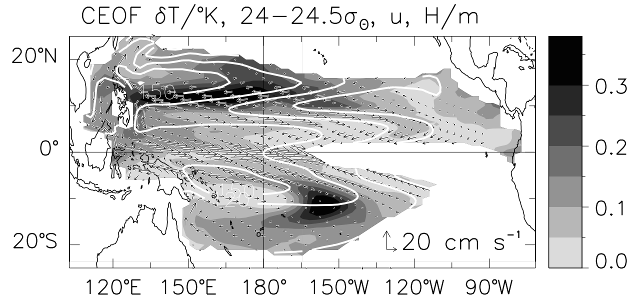

Figure 3. Absolute magnitude of leading CEOF of spiciness, as measured by temperature in °K between the 24.0 and 24.5 kg m^{-3} σ_Θ isopycnals. Magnitude is scaled by a standard deviation of the principle component and quantified by the gray scale on the right. Superimposed as white contours with an interval of 30 m are the time-averaged depth of this isopycnal layer. Arrows show the time averaged flow in m s^{-1} in this layer, with scale given in lower right corner. Note that the largest magnitude of the CEOF is achieved away from the surface at a depth in excess of 120 m, and that its equatorward spread follows the mean circulation.

affect, due to the strong vertical mixing and the shallow equatorial cell (McCreary and Lu 1994), surface budgets of spiciness in the equatorial outcrop regions at and east of the date line. This process leaves oceanic density unchanged, but perturbs the surface heat budget and thus the atmosphere. We hypothesize that this accelerates the southeast trades and breaks the balance between the wind stress and the oceanic pressure field as determined by isopycnal depths. As a result, the horizontal slopes of the isopycnal depth increase, the shallow equatorial cell accelerates and the equatorial cold tongue extends further to the west, all of which further intensifies the wind response and lead to surface fluxes of heat and fresh water that increase anomalies of spiciness in the western Pacific.

Associated anomalies of the wind stress curl off the equator cause anomalous advection on isopycnals and result at 10 to 15°S in warm spiciness anomaly whose arrival at the equator one to two years later further strengthens the atmospheric response. The acceleration of the currents at 10-15°N generate cool/fresh spiciness anomalies that initiate the opposite phase of the oscillation.

Alternatively, the variability presented here could be a passive oceanic response to internal variability of the atmosphere. The regular oscillation of spiciness with a distinct time scale of ten years (Figure 1) and spectral peaks at this period in precipitation, surface salinity, wind stress and other variables indicate that feedback processes are active. However, these peaks are not significant at the 90% confidence level and suggest that the spiciness mode is at best a damped mode excited by stochastic atmospheric forcing. A rigorous proof of the emergence hypothesis and rejection of the null hypothesis is the subject of ongoing work.

Discussion and conclusions

Advection of salinity compensated temperature anomalies along isopycnal surfaces sets the decadal time scale of the spiciness mode. Spiciness anomalies are generated at 10-15° latitude by anomalous advection, propagate with the mean circulation to equatorial outcrops in the central Pacific and affect the surface heat budget there. The resulting adjustments of wind stress and depth of the thermocline are hypothesized to exacerbate the initial response to the spiciness anomalies and lead to anomalies of the surface wind stress at 10-15° latitude of either hemisphere. Resulting anomalous currents on the southern hemisphere generate spiciness anomalies which, upon arrival on the equator via a direct, short path, provide a positive feedback. Current anomalies at 10-15°N generate spiciness anomalies by anomalous advection that reach the equator via the western boundary currents five years later and reverse the phase of the mode.

The spiciness mode has little expression in anomalies of sea surface temperature in the equatorial outcrop region due to two effects. First, the spiciness anomalies are mixed to the surface close to the border between cold tongue and warm

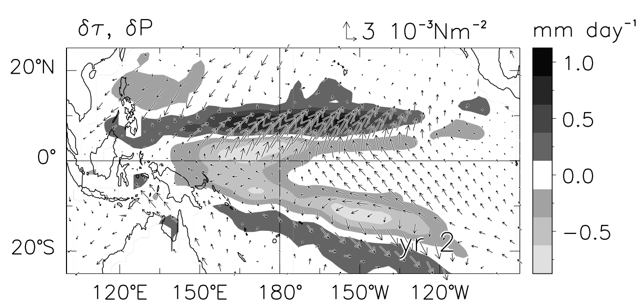

Figure 4. Reconstruction of wind stress (arrows) and precipitation (shading) for year 2 of the spiciness mode. Scale for the wind stress is given in upper right hand, the scale of precipitation is given by the gray bar on right, positive values correspond to anomalous strong rain. The panel was obtained by projecting simulated wind stress and precipitation onto the leading principle component of the CEOF of temperature on isopycnals (see Figure 3) and reconstructing one cycle as in Figure 2. The evolution of these atmospheric fields is a standing oscillation with largest values early of year 2, and close to zero in year 4.5 of the cycle of Figure 3.

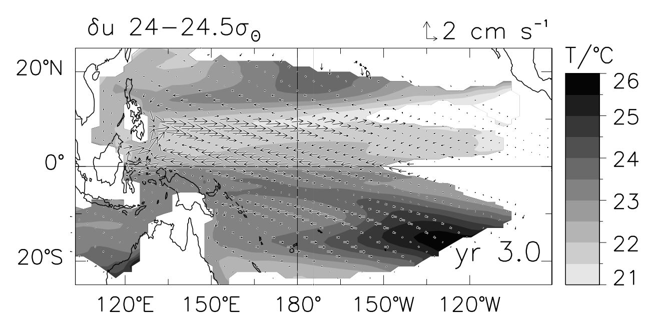

Figure 5. Reconstruction of oceanic velocity anomalies (arrows) in the 24.0 and 24.5 kg m^{-3} σ_Θ layer for year 3 of the spiciness mode (see Figure 2). Scale for arrows is given in upper right hand corner. Superimposed in shading is the mean temperature in the isopycnal layer showing the strong gradient between subducted warm waters north of 10-15°N, and cooler waters to the south. The warmest waters is 26°C on the southern hemisphere and close to 24°C on the northern hemisphere, see gray scale on right. Note that the anomalous flow crosses this mean gradient, and thus displaces this front in a region where the subsurface temperature anomalies on the isopycnals increase in strength (Figure 2).

pool, where vigorous atmospheric feedback efficiently vent perturbations of the surface heat budget to the atmosphere while leaving little trace in anomalies of sea surface temperature. Second, surface temperature in the cold tongue are predominantly affected by changes of isopycnal depth and outcrop position due to anomalies of the winds. If the initial tendency to surfacing warm (cool) spiciness anomalies is an ac–(de–)celeration of the trades, outcrop positions along the equator shift west–(east–)ward and anomalous cool (warm) surface temperature anomalies akin to a La Niña (El Niño) develop. These oppose and even overwhelm the heating(cooling) tendencies due to the surfacing spiciness anomalies.

The advection dynamics of the spiciness mode are similar to the hypothesis of Gu and Philander (1997). However, in the spiciness mode, temperature anomalies are generated on isopycnal surfaces in the thermocline by anomalous advection across the mean temperature distribution rather than by anomalous fluxes of heat at the surface of the ocean; advection from the southern hemisphere provides a positive feedback; and the dynamics of the mode reside entirely in the tropics, rather than couple mid-latitude and equatorial regions.

An observational test of the proposed dynamics requires the estimation of anomalies of oceanic isopycnal depths and spiciness on isopycnal surfaces. The lack of long-term, basin-wide observations of oceanic salinity limits analysis to a few CTD sections (e.g. Kessler 1999). These indicate that observed variability of temperature on isopycnals is indeed forced by anomalous advection, but the phasing of observed anomalies is not consistent with the coupled model results. Compared to nature, the coupled model likely overestimates the variance of the spiciness mode due to the overly strong temperature front on isopycnals at 10–15°N responsible for the generation of the anomalies, and due to an underestimation of the leakage of northern hemisphere waters to the Indonesian throughflow that allows for an efficient transport of anomalies to the equatorial outcrop regions. Finally, the far westward extent of the equatorial cold tongue and region of equatorial emergence of spiciness anomalies might critically affect the strength and sign of the feedback and adjustment of the coupled ocean-atmosphere system.

Sustained observations of salinity in the upper Pacific and investigations of the coupled response to the equatorial emergence of spiciness anomalies are essential to determine their fate in the tropical ocean, and their effect on El Niño and climate anomalies world-wide.

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