East Asian winter climate: an air-sea coupled view*

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Abstract

Observations and models show that sea-surface temperature (SST) front in East China Sea is coupled with northeast monsoon wind. Strong SST gradient anchors a cross-frontal recirculating wind over the front, resulting in the formation of low-hanging stratocumulus cloud band along the front and stronger northeast monsoon. The strong wind in turn favors onshore Ekman flux and intrusions of warm Kuroshio water, strengthening the SST front. The trend in the past decade and half has been for stronger front and northeast monsoon wind, as well as for more rain over northern Taiwan in winter.

* In memory of KK.

KK was kind and generous. Taiwan has lost a unique oceanographer who not only dedicated himself to scientific truths, but who also was selfless in sharing ideas and data. KK was a true Christian. If there was a time that I wanted to believe, then it was when I heard the sad news, that he had gone on, embraced in warmth where only persons like him could belong. That might be the only consolation I could have, knowing that he would be forever in peace. Yet it was hard, and I miss his friendship, and the intellectual discourse that we often shared.

Author and KK

A chat with KK

I came to know KK in 2011 when I accepted a visiting Professorship at NCU, though I had long before that heard about the man. Before I came, I made a conscientious effort in reading some of his papers, which to my great joy were meticulously well written and could be quite easily absorbed by a novitiate of biogeochemistry, as I was (and still am). The work portrayed a writer of no-nonsense precision and clarity. Our friendship was cordial but firm, perhaps because we were the most elderly members of the faculty, but really I suspected was because here was someone whose wide interests and curiosity emitted irresistible charm that resonates with anyone around him. On the celebration of the birthday of one of us in one wintry evening of 2011-2012 (see photo), as was often the case when we were with KK, our conversations turned into science. Upon my remonstration of the dreary and miserably continuous wet weather we had had for nearly 2 weeks, KK remarked that south of Taichung (a city in Central Taiwan) the sky was cloudless and the sun and moon were bright, as every Taiwanese school boy or girl surely knew. I was fascinated…; he suggested that I might like to "take a look" as to what and why that (the phenomenon) might be so. So here is a story of what became of that long-ago chat with KK.

Cloud band and SST in East China Sea

A beautiful cloud band in winter can sometimes be seen off the coast of China, nearly perfectly aligned along the mid-shelf of East China Sea into the Taiwan Strait (Fig.1). Winter overcast by stratocumulus clouds over this region is not unusual [Wood 2012]; nonetheless, the along-shelf alignment is quite remarkable. Underneath the cloud band, cross-shelf gradients of sea-surface temperature (SST; T) are very strong, with $|\nabla T| \approx 0.05\sim0.08\ ^{o}C\ km^{-1}$ comparable to values found in the Gulf Stream and the Kuroshio. Previous studies have identified the importance of SST fronts on winds [Chelton et al 2004; Minobe et al 2008]. Here we use analytical and numerical models [WRF; Michalakes et al. 2001] and observations to understand the processes that lead to the cloud-band formation, and examine the implications for winter climate in East Asia. The main results are summarized below. Details are given in Oey et al [2015].

Recirculating wind cell and monsoon wind

The strong SST front anchors a cross-frontal recirculating wind along the front, while warmer and moister air is sucked into the front, forcing convergence and updraft on the warm side, and low-lying cloud some ~2 km above the marine boundary layer (Fig.2). Above, the wind is poleward, strengthening the upper branch of the Hadley cell over this region, while the surface wind is equatorward into the Taiwan Strait, strengthening the lower branch of the Hadley cell.

Strong northeasterly monsoon carries cold air and preferentially cools the shallow waters near the coast, while simultaneously forces onshore Ekman transport and more frequent intrusions of warm Kuroshio water [Oey et al 2013; Wang and Oey 2014], thus increasing the cross-shelf SST gradient on the shelf. The atmosphere responds to the stronger shelf-sea front by developing along-front wind which reinforces the northeasterly monsoon near the surface, but is opposite at higher levels in the geostrophic interior of the troposphere – thus strengthening the regional Hadley cell. The stronger low-level wind further strengthens the front in a positive feedback. Data shows indeed that wind and SST front are coupled, so that years of strong front tend to correspond to years when the monsoon wind is strong, and *vice versa* (Fig.3). There is only a weak correspondence between El Nino and the coupled SST front-wind response, though the correlation with La Nina is somewhat stronger; the poor connection with ENSO suggests mechanisms that are distinct from those caused by ENSO. There are also long-term trends since 1999 of stronger SST front and winter monsoon wind. These trends are also remarkably coincident with the long-term onshore shift of the Kuroshio [Wang and Oey 2014].

Rain & climate in Taiwan

There are implications of the above results to regional ecosystem and climate, as stronger winter monsoon can initiate "cold SST surge" which may adversely impact fishery [Chang et al. 2004], and brings harsh wind and heavy precipitation to Taiwan. As pointed out by KK, people in Taiwan are familiar with generally wet and dreary winter in the north, and dry and sunny weather in the south. As surface wind converges over the SST front and strengthens in the Taiwan Strait, the flow is sub-critical (wind speed is less than the speed of mode-1 gravity wave) over the northern half of the Strait, but it accelerates to become super-critical downwind over the southern half due to the widening bend of the China mainland coastline near Xiamen (roughly directly across the strait from Taichung) (Fig.4). The northeasterly wind rapidly expands and marine layer thins in the southern half, yielding blue sky and starry night there that those unfortunate in northern Taiwan could only envy. Long-term wind and precipitation data (Fig.5) indeed show increased wind speeds and decreased precipitation from north to south along the strait, consistent with the theory. Model experiments with WRF demonstrate clearly that the sub-critical to super-critical transition is absent or becomes very weak if the SST front is smoothed and weak, supporting the idea that the SST front is important to the wind response.

In concert with long-term trends in the past one-and-a-half decade of increased strengthening of SST front and winter monsoon, data from TRMM also shows an increasing trend of precipitation in East China Sea and northern Taiwan during winter from 1999-2013 (Fig.6). What holds in future is anyone's guess, although in order to provide further dynamical insights, one could attempt to separate precipitation processes which are related to ENSO, and moreover could seek changes related to climate warming. Also, an attempt to relate the regional dynamics described herein to large-scale and global processes would provide a more complete picture [e.g. Oey et al 2013; Kug et al 2015]. Further studies are clearly necessary.

Epilogue

While the brief exposition above satisfied my curiosity – that the winter of 2011-2012 was in fact an anomalously wet one (Fig.6b) - I am quite filled with sadness that KK would not share the findings. Yet, I could not help but wondered if he might be looking over, satisfied, wearing that radiant smile which warmed us all in that cold and wet evening of winter of 2011-2012.

Acknowledgements

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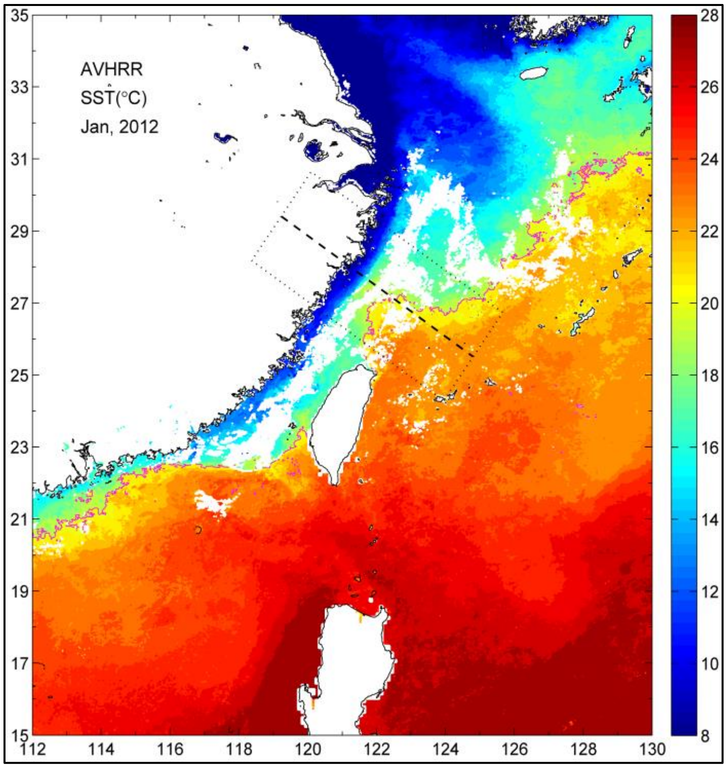


Fig.1 AVHRR SST [°C] composite for Jan/2012; white areas over ocean are clouds. Pink contour is 20 °C. Rectangle and dashed line in East China Sea are where winds and clouds are analyzed for the effects of the strong SST front, as summarized in Fig.2.

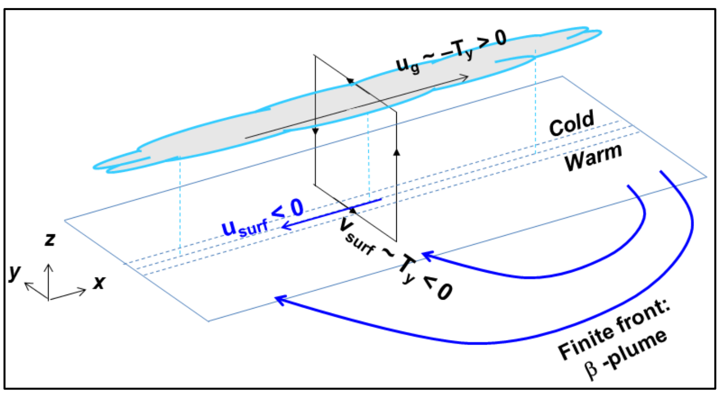


Fig.2 Winds and clouds over a strong SST front in East China Sea. Cross-frontal recirculating wind is forced by the SST front. Surface wind is sucked into the front on the warm side due to β-plume and turns equatorward along the front, into Taiwan Strait, while above (~2 km), outside the marine boundary layer, the wind is poleward and a cloud band aligned with the front is formed.

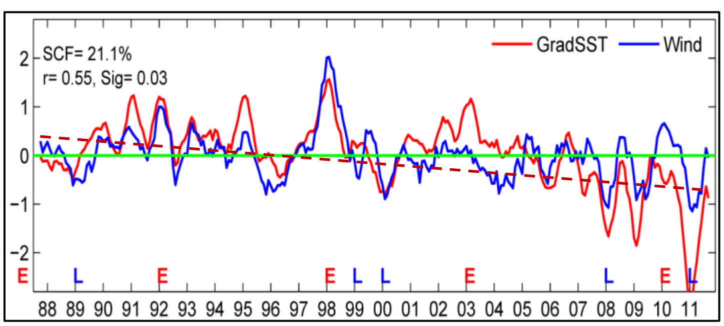


Fig.3 The SVD [Bretherton et al 1992] coupled mode between cross-shelf gradient of SST (red line; stronger if negative; dash is its trend; from GHRSST) and northeast monsoon (blue line; stronger if negative; from CCMP) in East China Sea: years of strong front and wind tend to coincide. “E” and “L” above the abscissa denote El Nino and La Nina years.

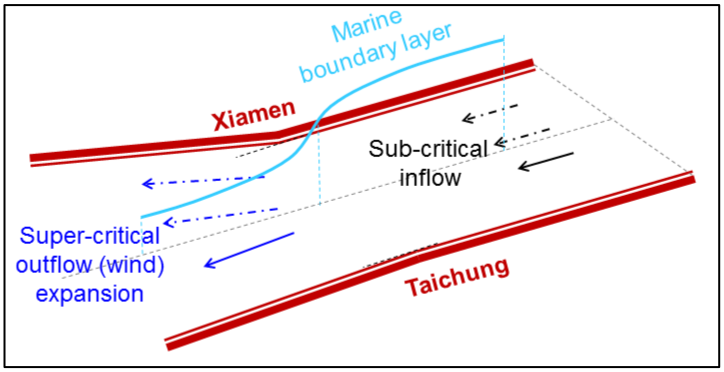


Fig.4 Northeasterly monsoon wind enters the northern half of the Taiwan Strait as a sub-critical flow with a thick marine layer (700~800 m) and expands as the coastline bends and strait widens in the southern half to become super-critical with a thin marine layer (~400 m), bringing dry and sunny sky to the southern half of the strait.

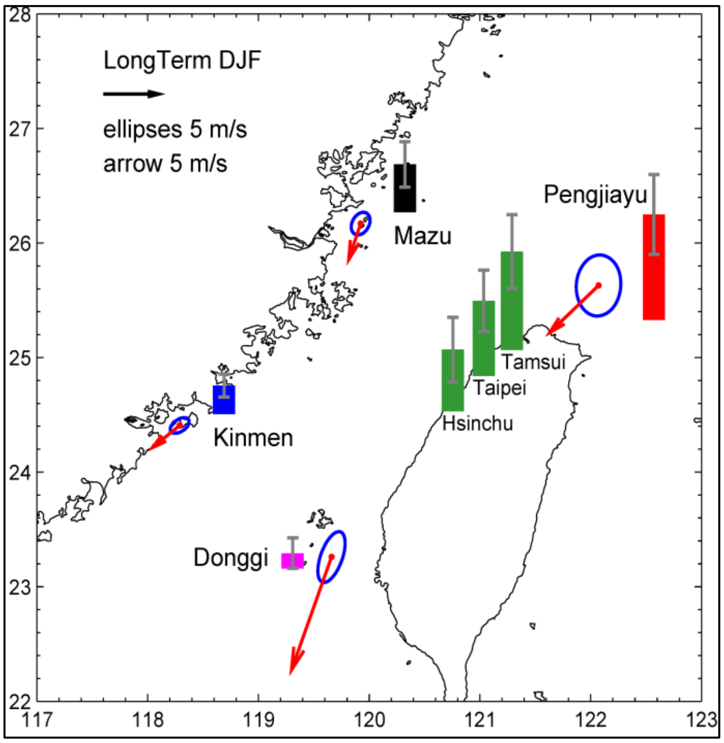
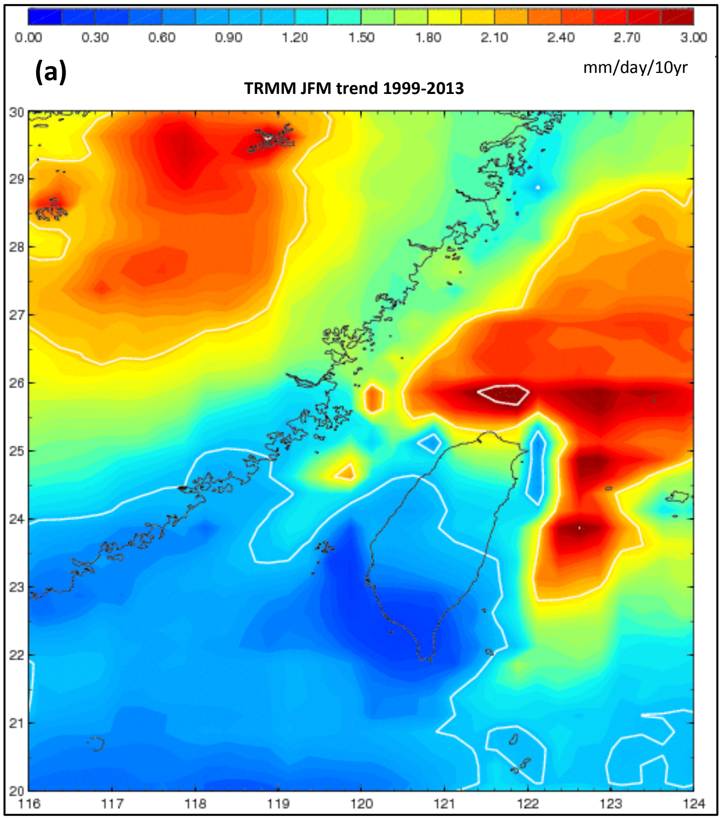


Fig.5 Observed wind (mean vector & variance ellipse) and mean precipitation (bars: red=4.6, black=2.1, blue=1.2, magenta=0.7, green=(2.7, 3.3, 4.3) mm day^{-1}) at Pengjiayu (1962-2014), Mazu & Kinmen (2005-2014), Donggi (1971-2014), Hsinchu (1991-2014), Taipei (1900-2014) & Tamsui (1900-2014) and StD (standard deviation).



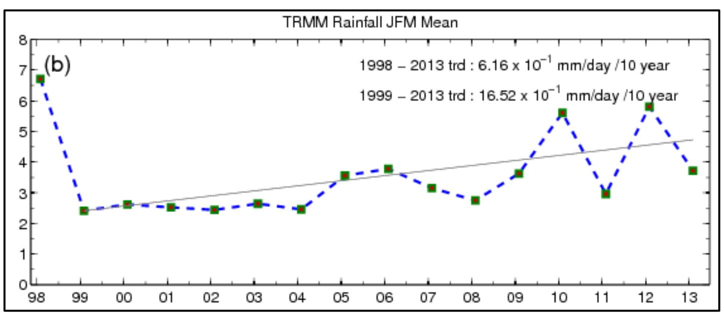


Fig.6 (a) TRMM precipitation trend from 1999-2013 (excluding the strong El Nino winter of 1997/1998). (b) The corresponding time series for data averaged over the East China Sea shelf and Taiwan Strait from 22.5^o N-30 ^{o}N. Note the large peak in the winter of 2011/2012.