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DIURNAL CYCLE OF SEA SURFACE WINDS AND TEMPERATURES DURING THE 2004 NORTH AMERICAN MONSOON EXPERIMENT

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1. INTRODUCTION

The 2004 North American Monsoon Experiment (NAME) Extended Observing Period (EOP) spanned 1 July - 15 August with the objective of exploring the large-scale circulation patterns and their diurnal variation over northwestern Mexico and the southwestern United States, and how they relate to the onset and evolution of the monsoon (Higgins et al. 2006). In this study, high-resolution oceanic surface winds and sea surface temperatures in the morning and afternoon will be used to examine features in the summer of 2004. The diurnal cycle in the Gulf of California (GoC) is especially interesting to study with high-resolution datasets because of the challenges faced in modeling the fine-scale structure and the significance in triggering Gulf Surges and even the North American Monsoon.

Previous studies have looked at the relationship between sea surface temperatures and monsoon onset (Castro *et al*. 1994, Mitchell *et al*. 2002) and at remotely sensed sea breeze diurnal cycles (Gille *et al*. 2003, Gille *et al*. 2005). This work is intended to build on them using higher resolution data and look at the diurnal cycle of sea surface winds (SSW) with sea surface temperature (SST) in conjunction.

2. SATELLITE DATA

The surface wind data are from the SeaWinds instrument onboard the QuikSCAT satellite, and are the Level 3 gridded product processed by NASA/JPL (JPL PO.DAAC Product 109). This is a polar-orbiting sun-synchronous platform, and as such, passes over roughly the same location on Earth twice daily. It has a nominal temporal resolution of 12 hours and a spatial resolution of 25 km. SeaWinds is an active microwave (13.4 GHz) scatterometer which transmits dual-polarized beams and receives backscattered power from the surface (Chelton and Freilich 2005). Land and ice are flagged for removal, but over water, centimeter-scale waves reflect radiation in a very useful fashion (i.e. Bragg scattering). A geophysical model function relates the received power to a 10 m equivalent neutral wind (Wentz and Smith 1999, Tang and Liu 1996). Rain roughens the ocean surface, and that effect cannot easily be separated from roughening caused by wind, so rain-flagged wind vectors are removed. The data are theoretically accurate to 2 m s^{-1} and 20°, with errors largely arising from rain contamination or directional ambiguities. In the region of interest, overpasses generally occur at approximately 0100 UTC (1900 LST, or evening) and 1300 UTC (0700 LST, or morning).

The sea surface temperature (SST) data used here are very high resolution: 1-hour temporal and 6 km spatial. They are derived from 5-channel GOES imagery (Legeckis and Zhu 1997), and processed by NOAA/NESDIS (JPL PO.DAAC Product 190). The brightness temperatures from the geostationary satellites are regressed against buoy observations to arrive at a SST. The GOES data are also corrected for sun glint and cloud cover, while land and ice pixels are flagged for removal. The data are accurate to 0.7°C, with errors largely arising from cloud cover, water vapor, and aerosols. To arrive at the diurnal cycle and to correspond with the QuikSCAT overpasses, only data from 0100 UTC and 1300 UTC were chosen.

3. SATELLITE OBSERVATIONS

The period of interest will be the NAME EOP, which was 1 July – 15 August 2004. This period, by no coincidence, spans pre-monsoon onset through maximum heating of the GoC, defined as the "warming phase" (Mitchell *et al*. 2002). During these six weeks, one can follow the evolution of SSTs, convection, and rainfall up from southwest Mexico, northwest Mexico and the GoC, and finally up to the southwest US, including Arizona and New Mexico (Mitchell *et al*. 2002, Mitchell *et al*. 2003, Ropelewski *et al*. 2005).

a. The Mean State

Figure 1 shows the mean state of SSW and SST during the NAME EOP. The prevailing northwesterly winds running parallel to the US west coast and then the Baja Peninsula flow over the cold California Current, around 20°C in summer. Then, at the southern tip of Baja, a bifurcation in the mean wind takes place, with a fraction of the flow continuing southeast, and a fraction turning east into Mexico, north, and northwest up the GoC. This is a fundamental ingredient for the monsoon. Since the GoC is fairly shallow and the SSTs are nearly homogeneous, there is very little upwelling or cross-gradient flow to be concerned with. The winds that wrap around the tip of Baja quickly warm and moisten and are largely responsible for daily convection over western Mexico and the southwest US (Douglas 1995).

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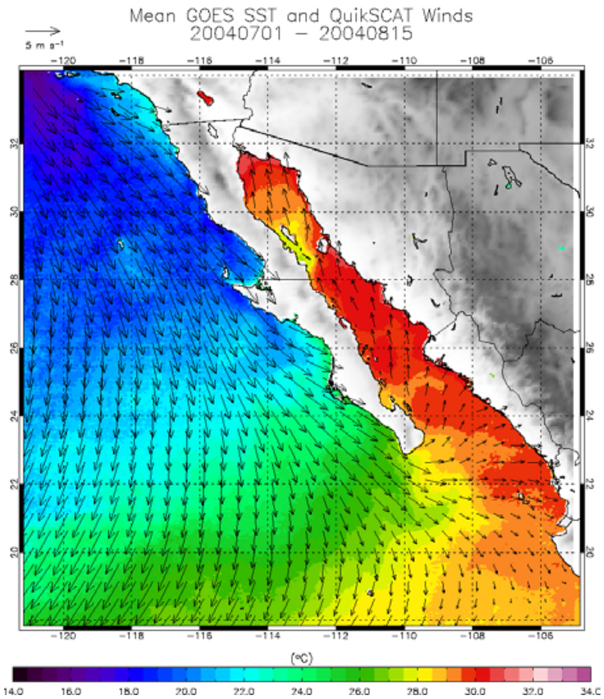

Figure 1: The mean sea surface temperature at 6km resolution derived from GOES imagery (colored contours) and the mean surface wind at 25km resolution from QuikSCAT (black vectors) in the period 1 July 2004 through 15 August 2004. Only every other wind vector is shown for clarity.

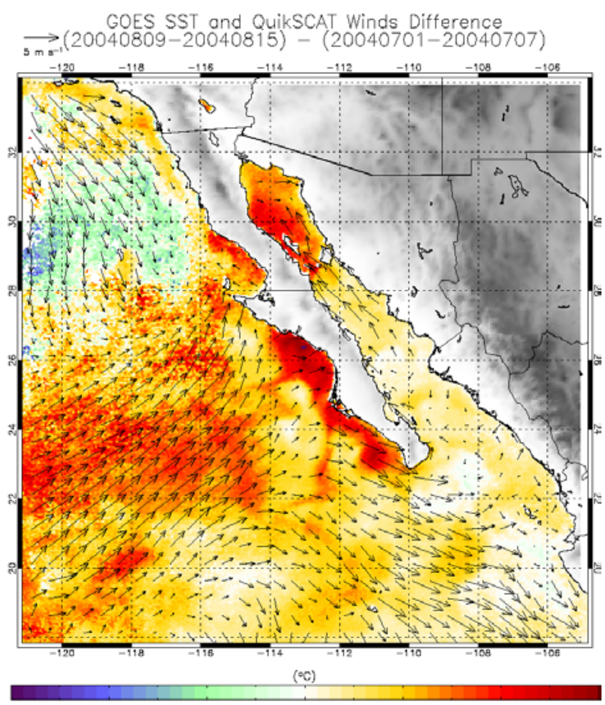

Figure 2: The difference in sea surface temperatures and surface winds between the last week of the NAME EOP and the first week of the NAME EOP (post- and pre-monsoon onset).

Figure 2 takes just the first week and the last week of the EOP and subtracts the first from the last, arriving at the change in conditions during that time. Most noteworthy is the substantial warming that occurs in the northern GoC and the surprisingly little warming that occurs in the southern GoC. On the Pacific side, there is a general warming west of southern Baja, and cooling west of northern Baja. The winds could partially explain this difference: during these six weeks, the northerly flow accelerates north of ~28N and decelerates south of ~28N; or this could be a result of shifting stratocumulus cloud cover and insolation. Also notice the increased southeasterly winds in the central GoC (around 5 m s^{-1}). In early July, there is not much of a coherent along-gulf flow, but in association with monsoon onset comes a steady (with intermittent gulf surges) along-gulf flow that pumps moisture into northwest Mexico and southwest US. As this flow intensifies and becomes more steady, the warming in the northern GoC mentioned earlier could partially be a "piling up" of warm water.

b. EOP Diurnal Differences

Summertime provides strong differential heating between land and adjacent water. During the day, the land rapidly heats, while the water temperature remains nearly constant. The cooler, denser air over the water flows inland. Then at night, the land radiationally cools to temperatures less than that of the nearby water. The cooler, denser air over the land flows offshore. To identify sea/land breezes using QuikSCAT data, one needs to utilize the different overpasses. The descending pass (sub-satellite point traveling southward) occurs at approximately 0100 UTC each day over the GoC, which is early evening local time. The ascending pass (sub-satellite point traveling northward) occurs at approximately 1300 UTC each day, which is early morning local time.

The land [sea] breeze does not occur at all locations at the same time; it takes several hours for the gravity current to propagate from the land [sea] to well offshore [onshore]. Gille *et al*. (2005) arrived at an average global land breeze propagation speed of 9 m s^{-1}, which agrees well with a theoretical value of 8 m s^{-1}. If the satellite passed over the GoC region at ~0600 UTC, the land breeze would have its strongest signal near the coast, with little signal farther offshore. However, 7 hours later (~1300 UTC), the leading edge of the land breeze should lie about 250 km offshore (Gille *et al*. 2003, Lerczak *et al*. 2001). Also of great influence in the timing of land/sea breezes is nearby topography (Dai and Deser 1999). The circulation is accelerated and amplified if substantial terrain is close to the coast, as it is in northwest Mexico. The Sierra Madre Occidental, or SMO, runs NW-SE along western Mexico and significantly affects rainfall patterns as well as the monsoon (Johnson *et al*. 2006).

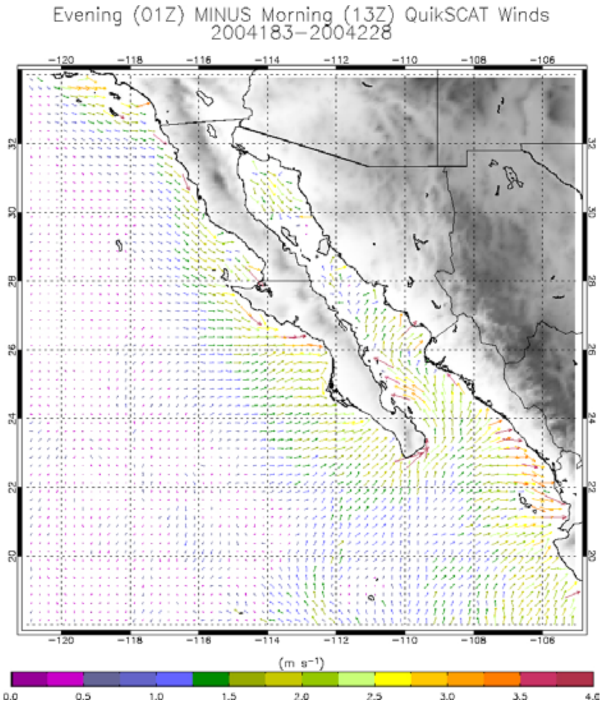

Figure 3: The average diurnal cycle of surface winds during the NAME EOP. The six weeks of QuikSCAT 1300 UTC passes are averaged together and subtracted from the same six weeks of QuikSCAT 0100 UTC passes averaged together.

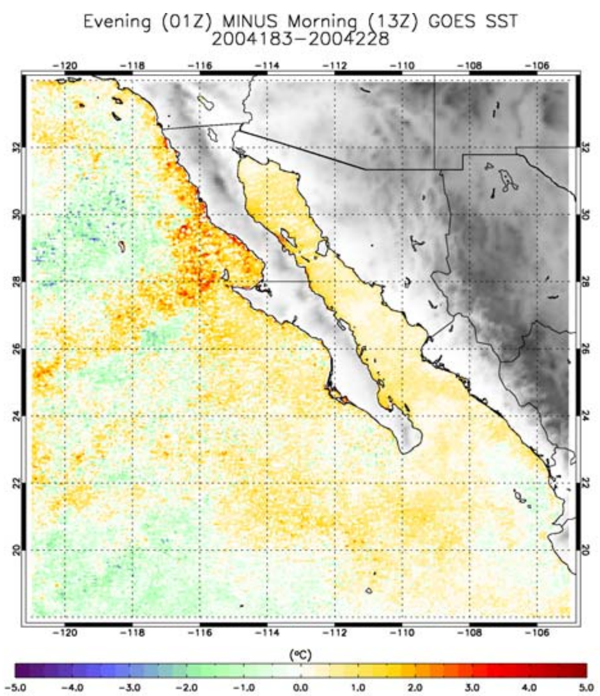

Figure 4: The average diurnal cycle of sea surface temperatures during the NAME EOP. The six weeks of GOES 1300 UTC images are averaged together and subtracted from the same six weeks of GOES 0100 UTC images averaged together.

In figure 3, the mean of all morning QuikSCAT passes is subtracted from the mean of all evening QuikSCAT passes during the six weeks of the NAME EOP. It reveals a clear sea breeze with an offshore extent of 300 km or more. The diurnal difference is most noticeable around the tip of Baja and where the SMO is closest to the ocean. There is enhanced convergent flow in the southern-central GoC during the evening. Figure 4 is the associated map of SST diurnal differences. When averaged over six weeks, there is a warming in the GoC from morning to evening (~1-2°C). The cooling centered at 21N 106W might be due to late morning rainfall and/or remnant anvils left over from morning convection in that region. Figures 5-8 will examine the diurnal variations of the SSW and SST before and after monsoon onset.

c. EOP Week 1 Diurnal Differences

For Figures 5 and 6, 0100 UTC data are averaged together and 1300 UTC data are averaged together for the first week of the EOP (1 – 7 July), which is just prior to monsoon onset. As before, the morning is subtracted from the evening. The land/sea breeze near the SMO is very intense and extends well offshore before the monsoon onset (which in 2004 was in mid-July in the GoC region). This time of year, solar insolation is maximized, plus there is little to no cloudiness/convection over land, so the land heats and cools very effectively, driving an intense land/sea breeze. In the extreme northern GoC, southeasterly flow weakens in the evening, resulting in northwesterly difference vectors. Johnson et al. (2006) document this stronger low-level jet in the morning in the northern GoC. During this first week, SSTs throughout the GoC warmed by 1-2°C between morning and evening, while even larger changes occurred over the Pacific Ocean west of Baja. Regions of coherent or spotty white pixels denote missing data, typically caused by cloud cover at 0100 and/or 1300 UTC. Persistent evening cloud cover was the culprit in the patch of missing data in the northern GoC during this week.

d. EOP Week 6 Diurnal Differences

Figures 7 and 8 show the diurnal differences in SSW and SST for the last week of the NAME EOP (9 – 15 August), which is a few weeks into the monsoon. In both fields, there is a muted diurnal signal. The land/sea breeze is much weaker and confined closer to the coast, while along-gulf southeasterlies strengthen in the evening. In the SST field, the Pacific Ocean generally cools from morning to evening, perhaps due to increased cloud cover in the evening. The GoC does not warm as much during a day in mid-August as it does in early July (only 0-1°C), owing mostly to decreased solar insolation. These figures qualitatively demonstrate that prior to monsoon onset, the diurnal cycle is more robust than after onset. After onset, solar insolation is somewhat reduced, the land is wetter, cloud cover is more frequent, all contributing to a moderation of the diurnal cycle.

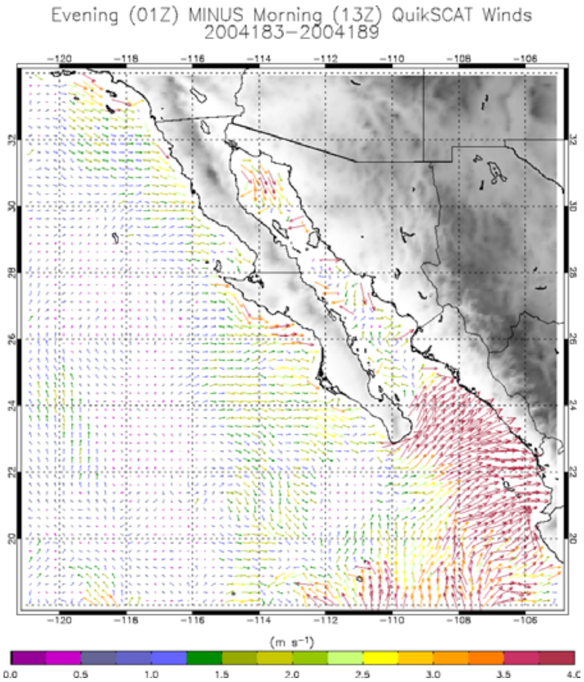

Figure 5: The average diurnal cycle of surface winds during the first week of the NAME EOP (1 – 7 July). The seven days of QuikSCAT 1300 UTC passes are averaged together and subtracted from the same seven days of QuikSCAT 0100 UTC passes averaged together.

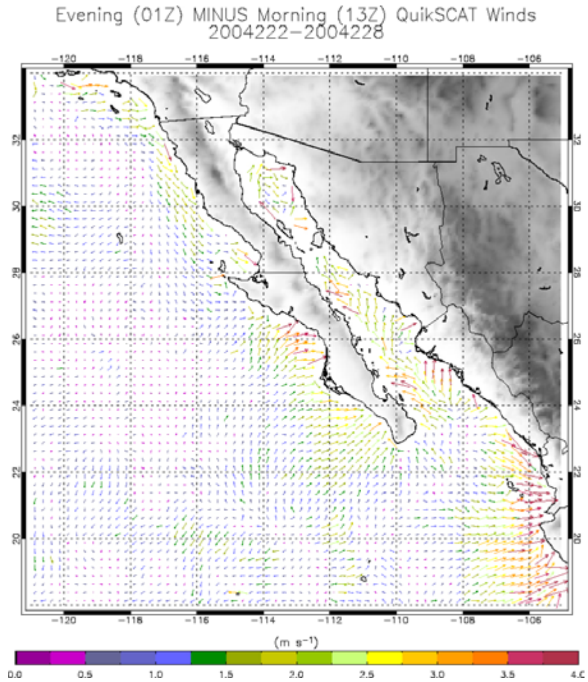

Figure 7: Same as Figure 5, but for the last week of the NAME EOP (9 – 15 August).

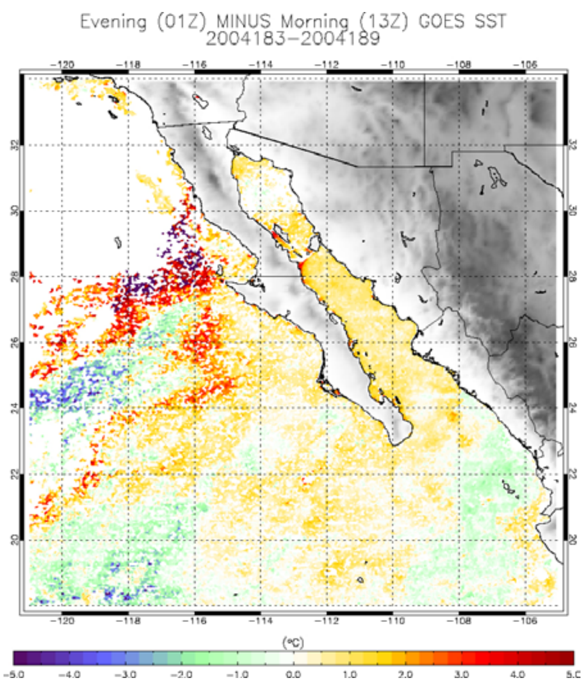

Figure 6: The average diurnal cycle sea surface temperatures during the first week of the NAME EOP (1 – 7 July). The seven days of GOES 1300 UTC images are averaged together and subtracted from the same seven days of GOES 0100 UTC images averaged together.

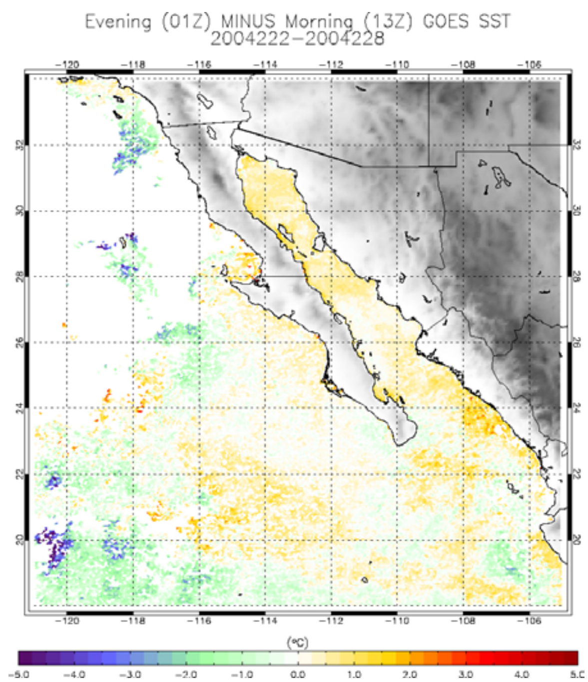

Figure 8: Same as Figure 6, but for the last week of the NAME EOP (9 – 15 August).

4. DISCUSSION

The Gulf of California region is a complex system with fine-scale processes that affect large-scale patterns. High resolution data are needed to observe these processes which eventually trigger the North American monsoon – a crucial part of the annual precipitation cycle in western Mexico and the southwest US. Indeed, high-resolution data do show features that could be important, but would be missed by lower resolution data. The SST evolution up the GoC is thought to be very significant in the timing of the monsoon onset, but gulf surges caused by pressure differences or tropical cyclones also play roles. This paper illustrates some of the differences in sea surface winds and temperatures between pre- and post-monsoon onset, as well as diurnal differences before and after the monsoon.

Prior to monsoon onset, the land/sea breeze is stronger along the entire coast, and as such, can extend farther offshore than it does after the monsoon. With less convection and more insolation, land surfaces respond rapidly to daytime heating and are also quick to cool at night, enhancing the land/sea breeze circulation. Upslope/downslope flow can be detected ~400 km offshore from the Baja Peninsula and SMO. Through the central and south GoC, there is not an organized or persistent flow between morning and evening. In the extreme northern GoC however, a persistent low-level jet is strong in the morning, then weakens by evening. This more dynamic timeframe is also evident in the diurnal changes in SST. Parts of the GoC warm and cool by ~2°C every day, while the Pacific Ocean west of Baja undergoes even more extreme diurnal temperature fluctuations

After the monsoon, southeasterly winds are present every afternoon/evening in the central and southern GoC, while SST increases more in the northern GoC. In the evening, the along-gulf winds are 2-3 m s^{-1} stronger than in the morning. The upslope/downslope signature can only be detected an average of ~250 km offshore, almost half the distance as pre-monsoon onset. The SSTs warm by ~1°C during the day in the GoC, but cool by ~2°C during the day over the Pacific Ocean. Not only is solar insolation less by this time of year, but the monsoon itself moderates the diurnal cycle via enhanced rainfall and cloudiness.

5. ACKNOWLEDGEMENTS

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