UNDERSTANDING AND PREDICTING COASTAL CIRCULATION BASED ON STRATEGICALLY LOCATED OBSERVATION STATIONS – AN EXAMPLE FROM THE SANTA BARBARA CHANNEL MODELING STUDY

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Summary

Limited resources often compel oceanographers to interpret circulation physics from a limited number of data - from which one can hopefully better assess the future states. It is of interest, therefore, given an ocean region, to allocate resources to observation moorings at locations that can potentially reap the maximum amount of information. For the Santa Barbara Channel (SBC), an east/west oriented channel (100kmx50km; northwest of Los Angeles, California) that forms the transition zone of southern and central California waters, the most important observations appear to be over-water wind stations west and east of the channel, and also coastal stations especially those on the channel islands. The reason is due to a close interplay between wind, windcurl and pressure gradient on synoptic time and small-spatial scales, the subject of this paper.

Introduction

As shown in the locator map in Figure 1, the SBC is nestled between the Southern California Bight (SCB) to its east, where waters are generally warm, and the Central California Shelf/Slope (CCSS) to the west, where upwelling produces cooler waters (Harms and Winant, 1998). The channel is modest in size, about 100km east/west and 50km north/south, and relatively deep > 100m. However, because of its unique locality off one of the world's most populated and pristine shoreline, environmental preservation is a top priority. For nearly a decade, the U.S. Minerals Management Service (MMS) and Office of Naval Research (ONR) have supported field and modeling research to attempt to understand and quantify the water circulation in the channel. Following a period of intense observations and modeling (especially for 1994-1997), from which much was learned (e.g. Oey, 1996,1999; Wang, 1997; Harms and Winant, 1998), a long-term circulation monitoring program is now planned with deployments of fewer measuring stations in the channel. The question is, where should one deploy measurements so as to adequately describe and predict the channel circulation? I will attempt to address this question from the perspective of dynamic modeling: by focusing on the role of wind forcings.

The south/southeastward wind at the western entrance of the channel is intense especially in summer (means of O(0.2-0.3 N/m^2; Dorman and Winant, 2000), but it decreases rapidly eastward over a distances of about 50km, due primarily to blockage of winds from the north by mountain range along the channel's northern coast. The resulting windcurl is often in excess of 0.1 N/m^2/100km. Moreover, the winds tend to be strongest at the channel's mid-axis and weaken north and south near the coasts (mainland to north and islands to south). One expects that these intense and small spatial-scale wind structures will affect in an important way the ocean response below. On a larger scale, the wind and windcurl also weaken equatorward from CCSS and Santa Maria Basin (SMB) to SCB, and we now have a fairly good understanding of how the resulting imbalance between wind forcing and windcurl-generated pressure gradient can generate seasonal vacillations of currents (Oey, 1996,1999). Given the intensity of the wind and windcurl over the smaller spatial scales of the channel, there is no reason why this imbalance cannot occur also on the synoptic time scales of O(days) (Oey, 1999).

Effects of Land & Island-Based Winds

Figure 2 compares the z=10m temperatures and currents of two model simulations each initialized from a state of rest with horizontally level isopycnals on Jan/16/1994, and integrated through May/16 (the figure shows the last 10-day averaged fields). In both simulations the large-scale wind is six-hourly from the European Center for Medium-range Weather Forecast (ECMWF), and the Princeton Ocean Model was used (www.aos.princeton.edu/WWWPUBLIC/htdocs.pom/). The large-scale wind is supplemented by, in Case A (left panel), winds observed at the over-ocean buoy stations (indicated by 4-pointed stars in Figure 1) and, additionally, in Case B (right panel), by winds observed on the land and island stations also (see Figure 1). These winds were kindly provided to me by Walter Johnson of U.S. MMS. For Case A, wind-weakening near mainland and islands, hence wind gradients (windcurls) at small-spatial scales, are absent. For Case B, such wind gradients are enhanced, resulting in a stronger cyclone in the western portion of the channel, a more developed equatorward current along the northern coast of the channel islands, and a well-defined poleward inflow of warmer waters at the eastern end of the channel.

Dynamics

It is not immediately obvious how stronger windcurls especially over the western portion of the channel can lead to a stronger cyclone and perturbations that penetrate to the east; yet an understanding of the dynamics is crucial in providing guidelines on where wind measurements should be set up in the channel so as to reap maximal predictive information from the model. I show now that the process involves trapped-wave dynamics forced by wind and windcurl.

Given that the wind has significant cross- and along-channel components, i.e. the wind is generally towards the southeast, it is instructive to consider separately effects of cross- and along-channel winds and then combine them. Figure 3 compares the 36-day averaged temperature and velocity fields, at z=-10m, of model runs forced by these three different channel winds, but initialized by an identical ocean at rest with vertical stratification derived from the annual mean density field. Note that in the absence of external forcing, the model ocean would remain at rest (and has been verified that indeed it did). In all three cases, the wind oscillates in time with a half sinsoid; thus, its amplitude varies like $\sin(2\pi t/P)$, for $2n\pi \le 2\pi t/P \le (2n+1)\pi$, and is zero for $(2n+1)\pi \le 2\pi t/P \le 2(n+1)\pi$, $n=0,1,2,3\ldots$, where $P=3$ days is the period. The spatial wind patterns are: (i) along-channel, eastward wind, maximum along the channel center axis, and Gaussianly decays north and south towards mainland (island), and also east towards the eastern entrance of the channel (left panel); (ii) across-channel, southward wind, maximum at the western entrance of the channel, and decays steeply (also in a Gaussian manner) towards east to become negligible over a distance of about 50km, and gently westward with a longer scale of 300km (middle panel); and (iii) southeastward wind, a combination of "i" and "ii" above (right panel).

Case (i) Along-Channel Wind (left panel of Fig.3):

In the absence of an eastward weakening in wind, a geostrophic, predominantly eastward, jet is produced beneath the wind profile. Non-Ekman (same below) cross-channel flows are also produced as a result of down(up)welling forced by windcurls on either side of the channel axis. These are small however, with maximum magnitudes < 0.5 mm/s, or one to two orders of magnitude smaller than cross flows due to pressure gradients I now discuss. The eastward weakening of the wind, or more precisely the windcurl, induces along-channel pressure gradients, equatorward (poleward) to the south (north) of the maximum wind axis, hence southward (northward) geostrophic cross flows to the south (north) of the axis. In the absence of coasts (main land to the north and channel islands to the south) these cross-channel flows would extend indefinitely south and north (there may be counter flows depending on the cross-channel *gradient* of the windcurl, but I will omit details here). The coasts give rise to along-coast currents, equatorward along the (north coasts of) channel islands, and poleward along the main-land coastline, forced by the interior along-channel pressure gradients – the dynamics of which is identical to that discussed in Oey (1999) in the so called Localized Transient or LT limit of short-time (days) and small-spatial (10's km) scales. (These currents are in addition to those that may be driven by near-shore, along-coast wind, which for simplicity I will assume to be nill.) These features can be seen in Fig.3. One sees warm (cool) water and high (low) pressure (as indicated by raised (lowered) sea-level) off SMOF (SMIN) (see Fig.1 for locations), and the accompanying equatorward (poleward) currents along the island (main-land) coast. Indeed, the equatorward currents extend further east to station ANMI despite very weak winds there, and currents along the main-land coast are poleward despite equatorward winds there.

Case (ii) Cross-Channel Wind (middle panel of Fig.3):

Without loss of generality, the cross-channel wind will be assumed to vary in the along-channel direction only. The case when wind also weakens near the coast north and south of the channel can then be easily understood. The curl due to the assumed cross-channel wind (nearly constant from over the open ocean to the west entrance of the channel, then decreases exponentially eastward to become negligible near the mid-channel) would produce a band of cool upwelled water spanning across the channel's west entrance, sandwiched between warmer waters west and east. Cross-channel currents are southward west of the band and northward east of it. In the absence of coasts, the band would extend indefinitely south and north. With coasts, trapped currents are formed along both coasts. The subsequent evolution that leads to a state which, despite the simple forcing, is remarkably similar to the SST often observed in the channel (Fig.3, middle panel). This state was brought about by two other mechanisms that cool the upper-layer waters west of the band. Firstly, vertical mixing is more intense because of stronger winds there, which brings cooler waters from below to the surface. Secondly Ekman transport brings westward cooler waters upwelled near the band's center. Thus west of the band cooler waters are advected southward and continue as trapped equatorward currents along the channel island coasts, while east of it warm waters are advected northward and continue as trapped poleward currents along the main-land coast. It should be pointed out that westward Ekman currents at z=-10m are significant (about -0.1m/s), and that currents in Fig.3 (middle panel) represent the net of Ekman plus pressure fields. The fact that the net along island coasts is eastward opposing Ekman indicates the dominance of the pressure field. Also, in contrast to case (i) of along-channel wind, the dynamics of which are basically linear involving trapped-wave currents along the coasts, case (ii) is non-linear consisting of mixing and advection of the density fields, as well as trapped-wave currents.

Case (iii) Combined Along- and Across-Channel Winds (right panel of Fig.3):

A comparison of this case with cases (i) and (ii) reveal that although nonlinear dynamics are important in (ii), the combined response (case iii) looks surprisingly like a superposition of (i) and (ii). Thus this case shows a cyclonic recirculation that extends from west to beyond the mid-channel. Clearly, the extent that the cyclone is formed, and the intensities of both the poleward and equatorward currents on the northern and southern coasts, respectively, are sensitive to details of the wind fields *within* the channel. The wind (and windcurl) over the poleward side of the channel and the existence of the channel islands as waveguide, are crucial in setting up currents perturbations in the equatorward side. While this may at first seem counter-intuitive, the dynamics are clear as I have explained above.

Conclusions

Small-scale wind and windcurl are crucial in driving synoptic currents in the SBC. In addition to the two NDBC buoy wind stations inside the channel, wind measurements on the two island-based stations (Fig.1) are necessary to provide adequate forcing to a predictive model, since these determine in large part the relative intensity of effects of wind and windcurl-induced pressure gradient forcings at a given time. Indeed, since the trapped-wave theory depends on these forcings, the island stations will play an important role in determining if a cyclonic or a unidirectional-flow state would prevail in the channel. This together with the large-scale wind and windcurl forcing that drive the longer-term currents would improve our ability to predict synoptic currents and mass fields in the channel.

Acknowledgements

This work was funded by the Minerals Management Service and the Office of Naval Research. I benefited from discussions with John Allen.

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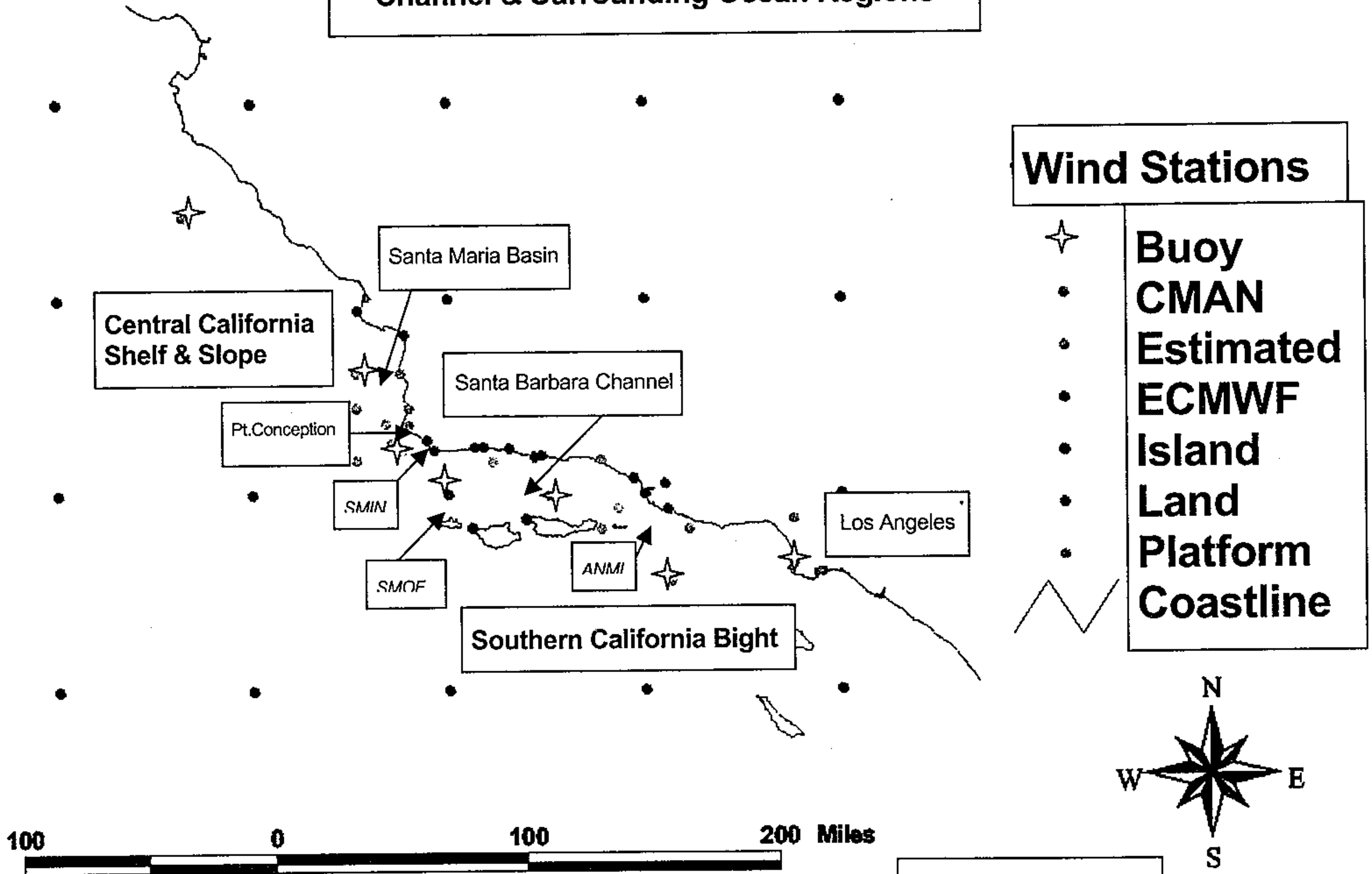
Figure 1. Locator Map of the Santa Barbara Channel & Surrounding Ocean Regions



Courtesy of Walter Johnson (U.S. MMS)

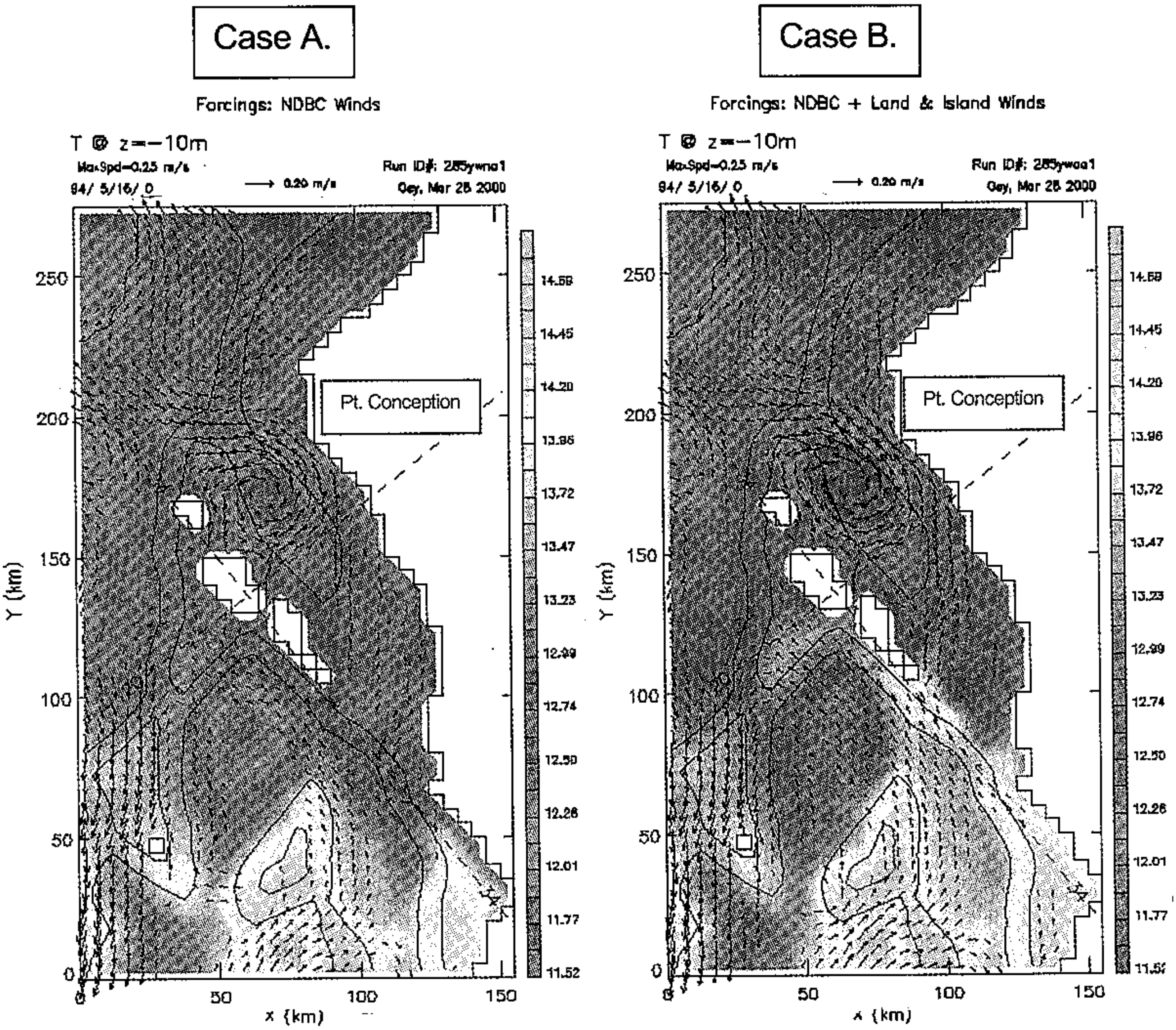


Figure 2. Averaged (May/06-16/1994) modeled temperature and velocity fields at z=-10m below the free surface for the case when only over-ocean (NDBC) buoy winds were used in the channel (left panel) and when both over-ocean and land and island-based wind stations were used (right panel) to force the model.

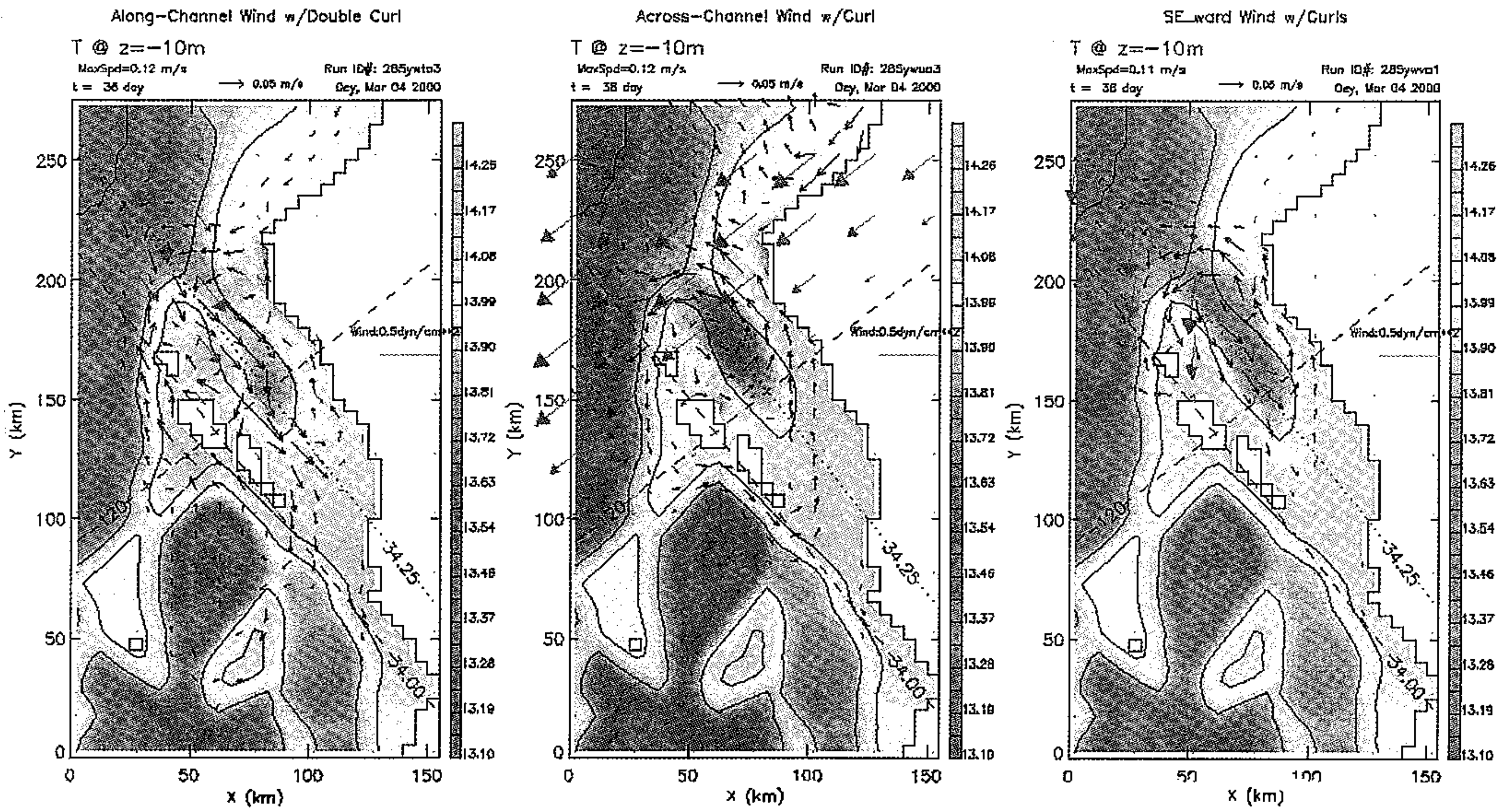


Figure 3. The 36-day averaged temperature and velocity fields, at z=-10m, of runs forced by 3 different channel winds as discussed in text.