# Development and Utilization of the Regional Oceanic Modeling System (ROMS)

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## LONG-TERM GOALS

Our long-term goal is the continuing evolution of the Regional Oceanic Modeling System (ROMS) as a multi-scale, multi-process model and its utilization for studying a variety of oceanic phenomena. The dynamical processes span a range from turbulence to basin-scale circulation. ROMS incorporates coupling of oceanic currents to surface gravity waves; sediment resuspension and transport; biogeochemistry and ecosystems; embedded large-eddy simulation; and mesoscale atmospheric circulation, as well as providing a framework for data-assimilation analyses. These activities are of interest to ONR through its core, DRI, and NOPP programs, including submesoscale parameterization (AESOP), strong internal waves (NLIWI), high-resolution air-sea interaction, tropical cyclones, community sediment transport modeling, and horizontal mixing.

## OBJECTIVES

Our objectives are continuing code developments and oceanographic simulation studies with the Regional Oceanic Modeling System (ROMS). The targeted problems are submesoscale wakes, fronts, and eddies; nearshore currents; internal tides; regional and Pacific eddy-resolving circulations and their low-frequency variability; mesoscale ocean-atmosphere coupling; and planetary boundary layers with gravity wave effects. To address these oceanographic problems our goals are to make ROMS more of a multi-process, multi-purpose model by including the coupling of the core circulation dynamics to the surface gravity waves; sediment resuspension and transport; biogeochemistry and ecosystems; large-eddy simulation (*i.e.,* Stanford's SUNTANS code); and mesoscale atmospheric circulation, as well as a framework for data-assimilation analyses. Our major algorithmic objectives are cross-scale grid-embedding in highly turbulent flows; an improved accuracy in the Boussinesq approximation with a realistic Equation of State (EOS); dynamically adaptive, vertical coordinates; surface-wave-averaged vortex force and Lagrangian transport; and the parameterization of wave-breaking and other mixing effects. Finally, we will further improve the pre- and post-processing tools and on-line documentation for ROMS.

## APPROACH

Computational simulation of oceanic currents and material distributions is an important and evolving tool in the geosciences. ROMS is a loosely coordinated modeling approach with a substantial international community of scientific developers and users (www.myroms.org). ROMS

is a generalized terrain-following coordinate, primitive-equation oceanic model that is implemented as a modern, efficient parallel code, and it is accompanied by an infrastructure of pre- and post-processing and visualization tools. ROMS provides a test-bed for some of the most innovative algorithms and parameterizations, and it probably is now the most widely used model among academic researchers for regional, high-resolution simulations of highly turbulent flows. At UCLA we are among the lead architects of ROMS. Our approach is problem-driven: the algorithmic formulation and code implementation are advanced to meet the requirements for simulating particular processes and phenomena. The results of the sequence of solved problems to date are indicated by the project publication list. The Principal Investigator is James McWilliams, and the Co-Investigator is Alexander Shchepetkin. The UCLA ROMS postdoctoral modelers involved in the various projects are Francois Colas (air-sea coupling, also Pacific and regional circulations, e.g., Peru and Prince William Sound, Alaska); Jeroen Molemaker (submesoscale advective processes); Yusuke Uchiyama (nearshore currents with waves and sediments); Maarten Buijsman (internal tides and nearshore currents); and Jaison Kurian (regional circulation, air-sea coupling). The graduate student researchers are Jun Hong Liang (shallow-water planetary boundary layer), Peng Wang (frontogenesis and frontal instability), and Carmen Lindsay-Hill (nearshore processes). Programmer/analyst Ed Huckle is working with Liang on the planetary boundary layer.

## WORK COMPLETED

### Algorithms and Codes

During the year 2007-2008 we have made several developments in UCLA ROMS codes, its algorithms, the associated supporting software and application practices, all of which are in line with our growing interest toward realistic simulations using sub-kilometer resolution, focusing on small-scale phenomena.

We made a revision of Boussinesq approximation – in essence a transformation of pressure and density (along the approach of Dukowicz, 2001), with a reformulation of the Equation of State of seawater (EOS). This allows us to eliminate most errors arising from an inherent contradiction associated with the use of a realistic compressible EOS in an incompressible Boussinesq dynamical model, while still capturing the physically important consequences of compressibility – thermobaricity and cabbeling. This study is now mature and resulted in Shchepetkin and McWilliams (2008a). In essence, this leads to re-evaluation of the role of EOS in oceanic modeling by de-emphasizing its traditional role of calculating the *in situ* density from the temperature and salinity fields (which are the model prognostic variables) toward its role of accurately translating the gradients of temperature and salinity into adiabatic gradient of density, and ultimately the fields needed by the model – pressure gradient force, vertical stability functions, and neutral slopes.

ROMS-family codes use several variants of mode splitting and time stepping algorithms, which is generally explained by specific needs by the research groups focusing on their different physical problems, as well as by the past evolution of the codes (resulting in branches, taking quasi-independent development paths). Although it was not our original intention, in March 2008 we felt obliged to respond to publication of Haidvogel *et al.* (20008), which we consider misleading, and wrote a correction note (Shchepetkin and McWilliams, 2008b) that provides an overview of existing time-stepping algorithms currently used by the different codes of the ROMS family. Our research on time stepping algorithms in ROMS have been expanded beyond Shchepetkin and

McWilliams (2005), resulting in Shchepetkin and McWilliams (2008c). This leads to a class of potentially useful two-time-level algorithms, which are more efficient than LF-AM3 stepping currently used in ROMS (however their practical implementation in a full-complexity code is not done yet).

Phase-averaged effects of surface gravity waves on slowly-evolving currents are now implemented both into barotropic (last year) and full 3D (this year) ROMS based on an asymptotic theory on wave-current interaction by McWilliams *et al.* (2004). This translates into the appearance of the additional mass and momentum flux terms (including vortex force, Bernoulli head, divergence of Stokes transport terms, *etc.* ) in the governing equations used in ROMS. This is coupled with modifying bottom drag formulation and near-bottom mixing, both of which are important for modeling sediment transport.

The vertical coordinate has been changed toward a hybrid system, which combines properties of sigma- and $z$-coordinates, with smooth transition between them. This leads to a controllable placement of vertical layers that are now more horizontal (aligned with free surface) in the desired upper portion of the water column (in practice the upper 300-500 $m$ chosen to match the main thermocline depth). The code, and the associated supporting software are now modified for the new coordinate, as well as to allow an easier change of this kind in future. This study was accompanied by showing that this change is beneficial for reducing the sigma-coordinate pressure gradient error. The majority of our simulations produced during the last year were done using the new coordinate.

UCLA ROMS's pre- and post-processing analysis tools have been significantly updated and expanded during the last year, resulting in a software package for grid generation and automated off-line nesting tools, which is now close to completion. This is a continuation of our study of nesting boundary condition and requires essentially two elements to succeed: (*i*) a robust model algorithm which guarantees acceptance by the model of the externally supplied data at the lateral open boundaries, and (*ii*) software to generate such data (usually via interpolation from a model solution on a coarser grid) in such a way that the data is as dynamically self-consistent as possible, so that the commonly observed artifacts associated with nesting can be avoided.

During last year we substantially reworked the parallel code structure of UCLA ROMS with the vision of achieving a more flexible approach toward irregular domain decomposition. We have abandoned the notion of "processor grid" in the physical code, which ultimately leads to a new standard in its framework. This also involves the revision of our approach to parallel I/O. The motivation is multi-fold, for example, there is no longer a need for the dimensions of physical grids to be evenly divisible by the number of subdomains in each direction. The model can be run now using subdomain partitions (tiling) inside each MPI-subdomain to optimize utilization of processor cache, as well as optimize communications via message passing by reducing the probability of a situation where multiple CPUs (CPU cores) belonging to the same physical node try to send messages simultaneously, thus competing for access to the network interface shared by the multiple CPUs (cores) on the node. The code now allows hybrid parallelism (having multiple Open MP threads within each MPI node), provided that MPI implementation is thread-safe.

We continue to collaborate with Oliver Fringer and Bob Street (Stanford) on the embedding of the non-hydrostatic, finite-element SUNTANS code in ROMS. A prototype configuration is being used to simulated tidal flows off Northwest Australia, and a new configuration is being designed for eddy-tide interactions around Monterey Bay.

**Circulation Phenomena**

*Submesoscale Flows and Lateral Mixing:* Oceanic processes at spatial scales between $10\ m$ and $10\ km$ and temporal scales, ranging from hours to days, are still poorly understood. Particular interest in lateral mixing at these scales stems from observations of rapid tracer dispersal in the coastal and open ocean. In the submesoscale regime, the traditional paradigm of separating motions into geostrophic eddies that dominate lateral transport and microscale turbulence that dominates vertical mixing is no longer appropriate. We are studying frontal processes at multiple scales, loss of balance through ageostrophic instabilities, and forward energy cascade to micro-scale dissipation and mixing (Capet *et al.*, 2008c-e; Molemaker *et al.*, 2008a-b; McWilliams *et al.*, 2008b). Figure 1 is an illustration from a new study of submeoscale currents off South America.

*Nearshore Wave-Current Interaction:* Surface wave effects have been incorporated into ROMS as described above. The dynamical equation for infragravity waves driven by primary short waves derived in McWilliams *et al.*(2004) is implemented in a barotropic ROMS to investigate generation and propagation of infragravity wave in the deep ocean in the context of seismic hum excitation (Uchiyama and McWilliams, 2008). Effects of wave-current interaction on the nearshore shear instability in breaking-wave-driven alongshore currents have been investigated with a depth-averaged configuration as shown in Fig. 2 (Uchiyama *et al.*, 2008). We are currently examining fully 3D problems for both idealized and realistic beach shapes (Duck, NC; Martha's Vineyard, MA; and Palos Verdes, CA). The wave fields are determined by either the WKB equation or through coupling to the SWAN wave model (Booij *et al.*, 1999).

*Generation and Evolution of Nonlinear Internal Waves in the South China Sea:* The nonhydrostatic Regional Ocean Modeling System (ROMS) is applied to study the generation and evolution of nonlinear internal waves (NIWs) or solitons in the South China Sea (SCS). The model results reveal that the westward propagating solitons are generated due to a combination of internal tides and lee-beam release. In the model, the Luzon ridge near the Batan Islands is represented by a (Gaussian) ridge with similar height and stratification as in the SCS. The model is forced by an (asymmetric) oscillating barotropic and/or steady current at its eastern boundary. The model is in the regime in which NIWs and lee waves are generated. The first-mode wave is initiated by a westward-leaning lee beam due to the eastward tidal current over the ridge. As soon as the eastward flow decelerates the lee beam is released, forming the first-mode front that evolves into a soliton wave form (Fig. 3). Analysis reveals a beating between the barotropic tide and the first mode in the far field, as well as a beating between the first and higher modes. The residual velocity field portrays flows at the surface away from the ridge, flows below the surface towards the ridge, upwelling near the tip of the ridge, and downwelling at the toe of the ridge (Buijsman *et al.*, 2008).

*Pacific and Regional Circulations:* In eastern boundary upwelling regions, where the mean circulation is generally weak, eddy fluxes can potentially influence dynamical balances. It was recently shown that these regions are a large source of bias in global coupled model solutions (Large and Danabasoglu 2006), suggesting an important upscaling effect. We also know that regional mesoscale activity can be influenced by large (basin) scale signals (a downscaling effect). In this context we focus on both downscaling and upscaling processes with ROMS configurations for the U.S. West Coast (USWC) and the Peru/Chile Current system (PCS). Emphasis is put on the PCS due to its direct connection with the equatorial region; this makes it a good testbed for Pacific signal downscaling (*e.g.,* ENSO). Taking advantage of our effort to improve downscaling techniques and

boundary conditions treatment in ROMS (Mason *et al.*, 2008), we developed a set of embedded ROMS grids in the PCS (Fig. 4). A detailed study of the 1997-98 El Niño has been carried out for both the PCS (Colas *et al.*, 2008) and the USWC (Kurian *et al.*, 2008). Mesoscale eddies play a prominent role in maintaining the heat balance between surface heating and coastal upwelling cooling, and they show appreciable low-frequency variability through downscaled climate variability (Capet *et al.*, 2008b,f). In the offshore regions we find an eddy cooling equivalent to -30 W $m^{-2}$, which indicates a likely upscaling effect on the atmosphere.

*Planetary Boundary Layers:* In a long-standing collaboration with Dr. Peter Sullivan (with separate ONR funding at NCAR), we participate in Large-Eddy Simulations (LES) of both the atmospheric and oceanic planetary boundary layers, especially focusing on the influences of surface gravity waves on each (*e.g.,* Sullivan *et al.*, 2007a,b), and how they may be represented in the K-Profile Parameterization (KPP). In the oceanic layer breaking waves and Langmuir circulations increase the turbulent mixing and stratified-entrainment levels quite substantially, especially under high winds. In the atmospheric layer wave-pumping carries the surface stress through a wavy layer into the more familiar Monin-Obukhov layer above, and — with old swell waves or misaligned winds and waves — the surface stress reshapes the wind profile throughout the layer and creates a mid-level jet. Using the KPP model we have shown how unresolved temporal fluctuations in the surface wind stress and buoyancy flux induce time-averaged changes in the Ekman boundary-layer currents (*i.e.,* rectification: McWilliams and Huckle, 2006; McWilliams *et al.*, 2008a). With Sullivan we are examining surface wave effects on the response to a hurricane with high winds, high waves, and inertial-resonance due to wind veering.

*Air-Sea Coupling:* Eastern boundary upwelling regimes have a clear regional coupling among the alongshore winds, cold ocean waters, and stratus clouds, and they probably also have a significant mesoscale coupling associated with the abundant surface fronts. We are developing a coupled configuration for the Weather Research and Forecast model (WRF) and ROMS in collaboration with Prof. Alex Hall (UCLA) and have configured it for both California and South America (the site of the CLIVAR VOCALS experiment). In the meantime, as a first step toward more complete coupling studies, a wind/SST empirical coupling, based on recent satellite observations (Chelton *et al.*, 2008), was implemented in ROMS. One of our objectives is to get a better sense of the nearshore wind structure. It is well-known that winds from large scale atmospheric models or satellites, which are the usual sources of model forcing, do not resolve the nearshore wind drop-off that occurs in reality. Numerical simulations of the Peru/Chile (PCS) and the California (CCS) upwelling systems are being currently analyzed. The wind/SST feedback leads to reduced nearshore winds and warmer nearshore SST. This reduced coastal wind strength reduces the cold bias in nearshore SSTs and significantly modifies the upwelling structure and the larger scale quasi-equilibrium model solutions both for the Peru/Chile and the USWC 4. More subtle effects of the wind/SST coupling on the mesoscale eddy activity are now investigated.

## RESULTS

Since funds for this grant were received late in the year, we defer until the next report a more extensive discussion of results beyond their brief mentions in the preceding section.

## IMPACT/APPLICATIONS

*Geochemistry and Ecosystems:* An important community use for ROMS is biogeochemisty: chemical cycles, water quality, blooms, micro-nutrients, larval dispersal, biome transitions, and coupling to higher tropic levels. We collaborate with Profs. Keith Stolzenbach (UCLA), Niki Gruber (ETH), Curtis Deutsch (UCLA), and David Siegel (UCSB) on these topics.

*Data Assimilation:* We collaborate with Drs. Yi Chao (JPL) and Kayo Ide (U. Maryland) by developing model configurations for targeted regions and by consulting on the data-assimilation system design and performance. Current, quasi-operational, 3DVar applications are in Monterey (AOSN, ASAP), California more broadly (SCCOOS and CenCOOS), and Alaska (Prince William Sound). We are starting to develop the Local Ensemble Transform Kalman Filter technique — a more efficient alternative to 4DVar methods with most of the benefits compared to 3DVar — to obtain solution-adaptive, time-evolving estimations with ROMS.

## TRANSITIONS

ROMS is a community code that has widespread applications (http://www.myroms.org).

## RELATED PROJECTS

The Community Sediment Transport Model (CSTM) is a NOPP and ONR project that is based on ROMS. We are participating as code prototypers and application testers.
Three Integrated Ocean Observing System (IOOS) regional projects for California and Alaska (SCCOOS, CenCOOS, and AOOS) are utilizing ROMS for data assimilation analyses and forecasts.
We are participating in VOCALS, which is a CLIVAR and NSF project to investigate coupled regional climate processes of the west coast of South America.

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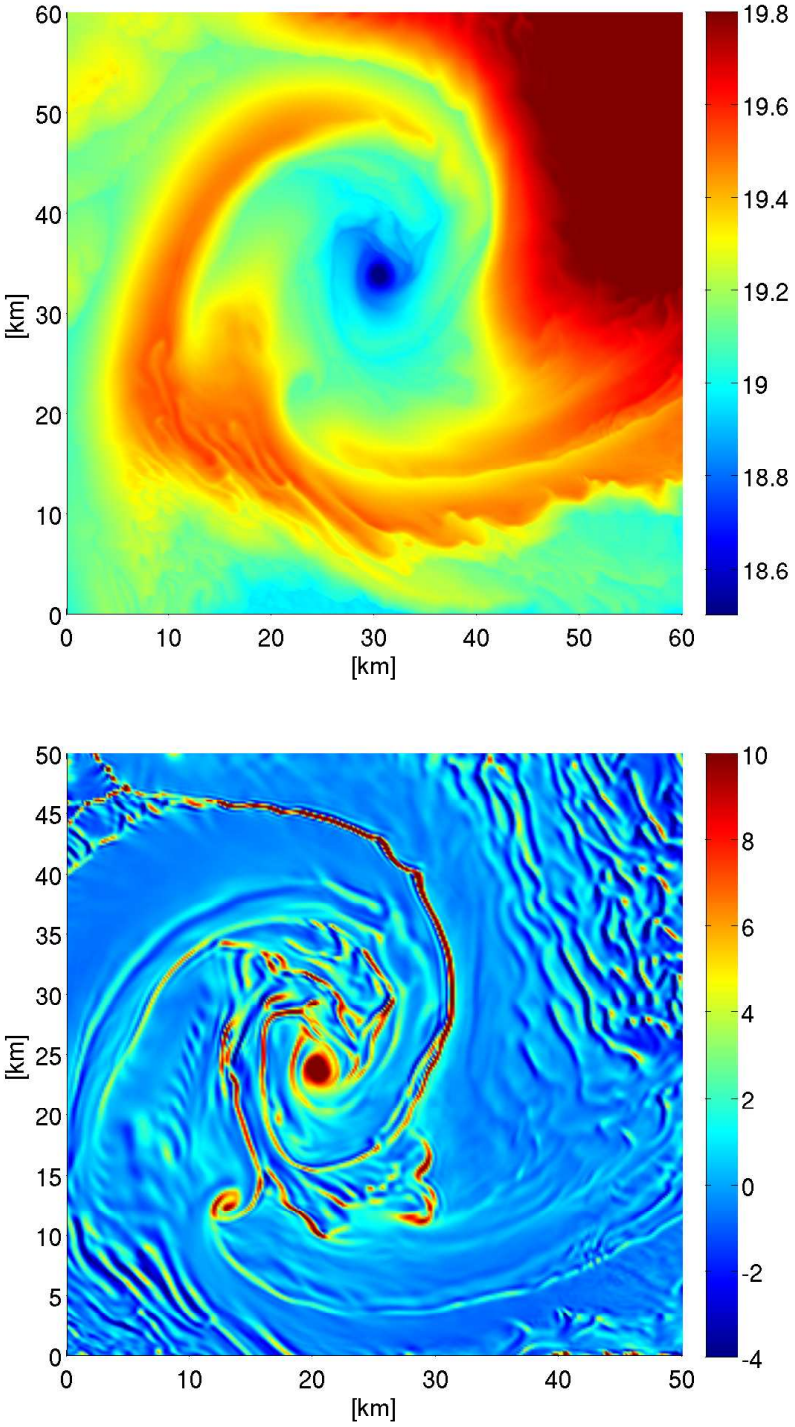


Figure 1: Snapshot of the SST (top) and vertical component of vorticity at the surface (bottom) in finest grid of the nested solution in Fig. 4. Shown is a spiral eddy structure that is wrapping up temperature fronts undergoing active frontogenesis and sheets of positive vorticity. The numerical grid used to obtain this solution utilizes $974 \times 696 \times 84$ grid points with an horizontal resolution of $180\ m$. The figure zooms in on a $50\ km$ by $50\ km$ region within the computational domain around $13^o\ S$, $80^o\ W$.

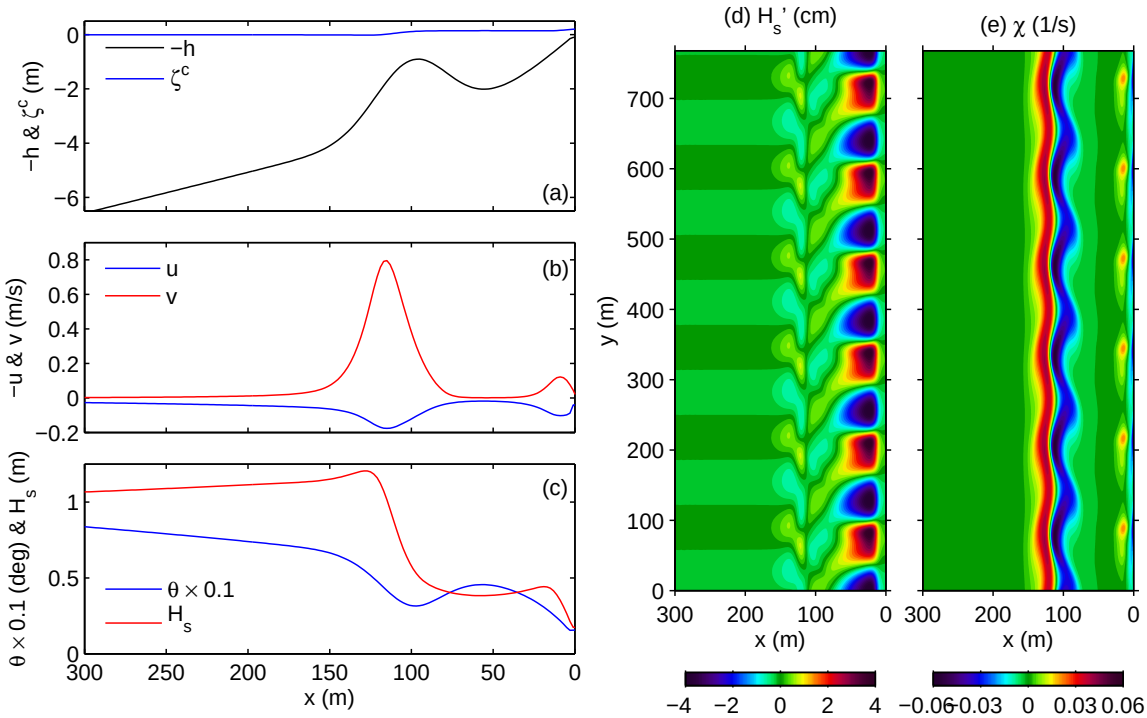


Figure 2: Example of wave-current interaction in littoral-current shear instability on an idealized barred beach in a marginally unstable flow regime. Cross-shore profiles of time- and alongshore-averaged (a) sea surface elevation $\zeta^c$ and depth $-h$, (b) shoreward and poleward velocity components $u$ and $v$, (c) wave direction $\theta$ and R.M.S. wave height $H_s$. Also shown are plan-view snap-shots of (d) fluctuating component of wave height $H_s''$ and (e) vertical component of relative vorticity $\chi$.

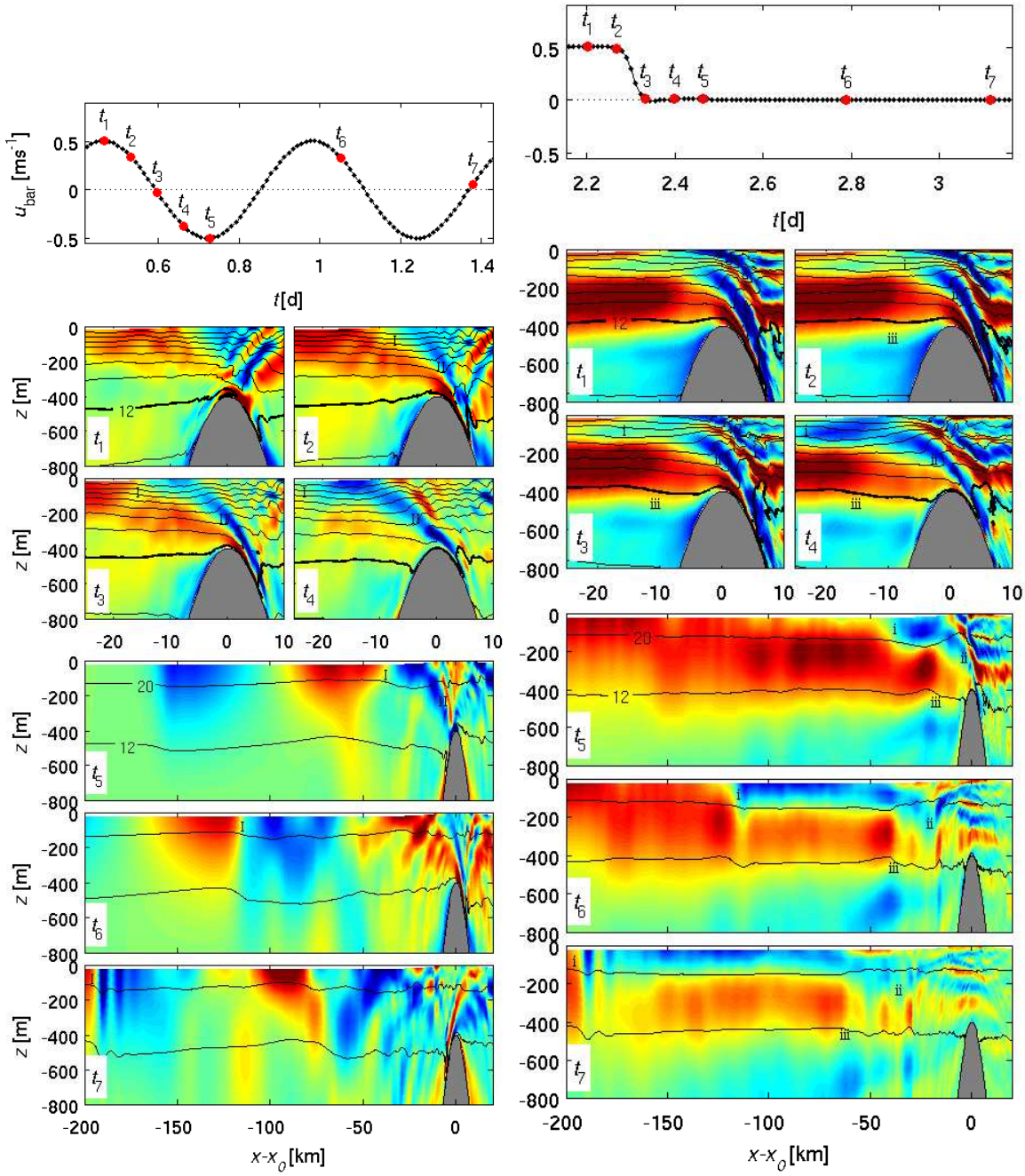


Figure 3: The lee-wave release mechanism for oscillatory flow (left panels) and for rightward steady flow of 0.5 ms$^{-1}$ that then abates (right panels). The top panels show the barotropic velocity at the mount and the red dots mark the seven snapshots shown in the bottom panels that show baroclinic velocity (colors) and isotherms. The warm (cold) colors indicate eastward (westward) flow. The panels for $t_1 - t_4$ feature isotherms in 2°C increments. The letters I and i mark first mode waves and II, ii, and iii mark higher mode waves. At $t_7$, the first mode waves carry a soliton packet.

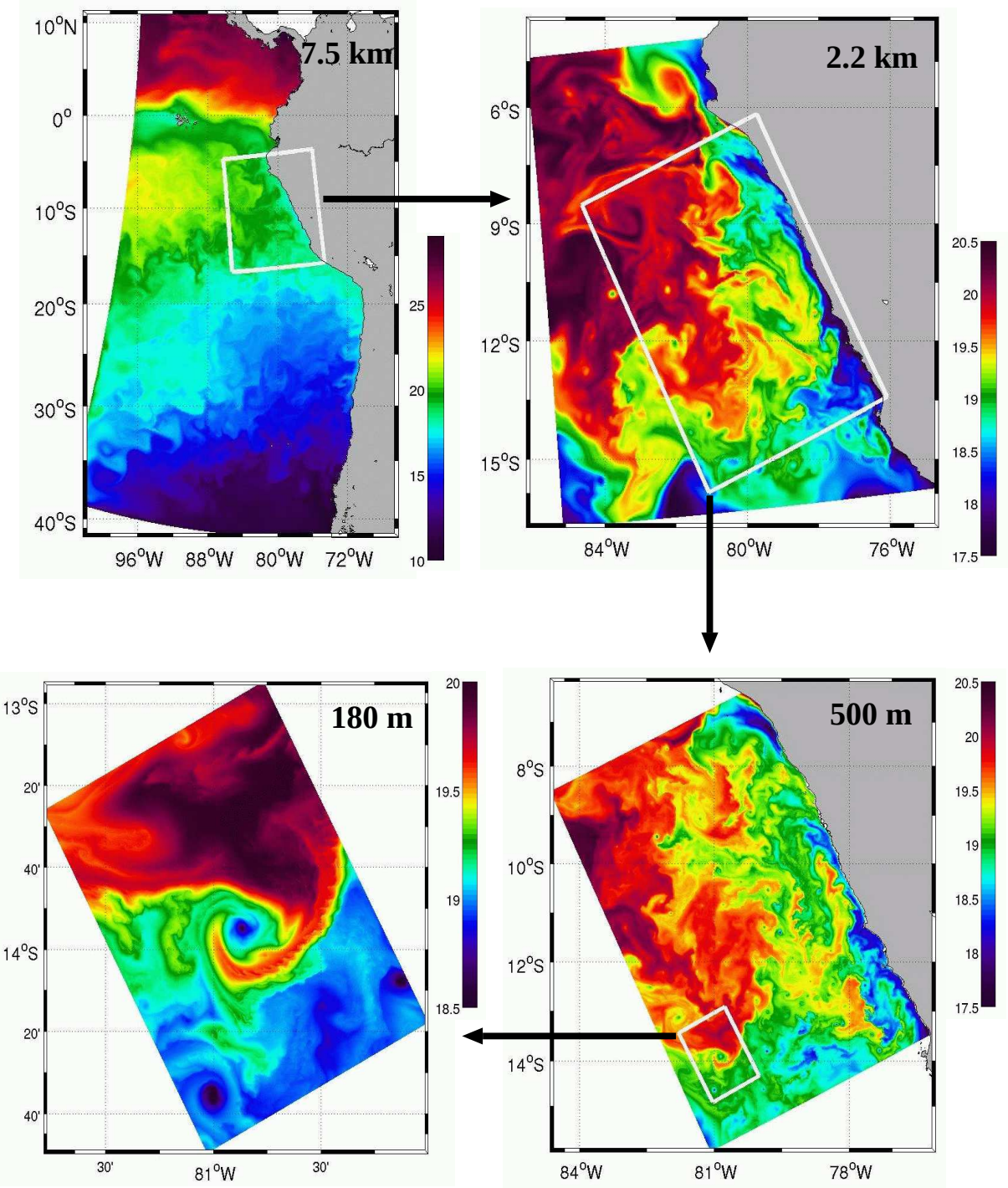


Figure 4: A wintertime snapshot of Sea surface temperature in the South Eastern Pacific. A nested grid hierarchy is employed with horizontal resolutions of 7.5, 2.2, 0.5 and 0.18 km.