### *C. Biochemical-Physical Smoothing in Massachusetts Bay*

A joint estimation of biochemical-physical variabilities and uncertainties in Massachusetts Bay is carried out via ESSE for the late summer of 1998. It is based on multiscale interdisciplinary data sets collected during the Littoral Ocean Observing and Predicting System (LOOPS-98) experiment. The LOOPS-98 scientific focus was phytoplankton and zooplankton patchiness, in particular, the spatial variability of zooplankton and its relationship to physical and phytoplankton variabilities. Synoptic physical and biochemical data sets were obtained simultaneously over a range of spatial and temporal scales. Real-time interdisciplinary nowcasts and forecasts were issued [1] and quantitative adaptive sampling was carried out [10]. The focus here is on the ESSE smoothing during the Aug. 25–Sep. 2, 1998 period.

*Biochemical and Physical data.* During LOOPS-98, observations were gathered on multiple scales using ships and Autonomous Underwater Vehicles. The gathering occurred in three phases: the initialization surveys (17–21 Aug.), update surveys (2–4 Sep.) and two weeks of intensive operations (17 Sep.–5 Oct.). The main physical data consisted of temperature and salinity profiles at Bay-scale, mesoscale and sub-mesoscale resolutions. For the ecosystem, profiles of chlorophyll-a fluorescence and light levels, and bottles of nitrate, ammonium, chlorophyll-a and pheaopigment, were collected at mesoscales and sub-mesoscales resolution in Cape Cod Bay and at mesoscale resolution north of Cape Cod Bay. The Massachusetts Water Resources Authority (MWRA) also collected biochemical samples which are employed here.

*Coupled Ocean Physics and Biochemical Models.* The ocean physics model is the primitive-equation model used in Sect. III.A. Here, it is coupled to a biochemical model which governs the interactive evolution and spatial distribution of phytoplankton, zooplankton, detritus, nitrate, ammonium and chlorophyll-a (Chl-a). The model is nitrogen-limited: fluxes and state variables are expressed in terms of nitrogen ($\mu$ *mol N/l*) except the Chl-a compartment which is in (*mgCh/m*$^3$). For all biochemical state variables, a four-dimensional advective-diffusive-reactive equation is employed. The model parameters were estimated from a combination of *in situ* data, literature surveys and approximate dynamical constraints. After the real-time cruises, a wide range of parameter values were investigated and the optimal values found are used here. Further details on model parameters and structures are given in [1].

*ESSE smoothing.* The biochemical-physical fields and their dominant errors are first initialized. This initialization is carried out following the 3D methodology of [9] (as in Sect. III.A), using the above interdisciplinary data and dynamical models. Presently, only the period Aug. 25–Sep. 2 of the ESSE simulation is discussed. The results of the coupled dynamical forecasts and of the assimilation via ESSE filtering and ESSE smoothing backward in time are illustrated on Fig. 8.

The nowcast on Aug.25 (Fig.8a) clearly indicates patchiness in the Chl-a field. At the end of the 1998 summer, the Chl-a maxima are around 4–7 *mgChl/m*$^3$ and located near 20 m depth. As September nears, storms of increasing strength and frequency pass over the region, sub-mesoscale and

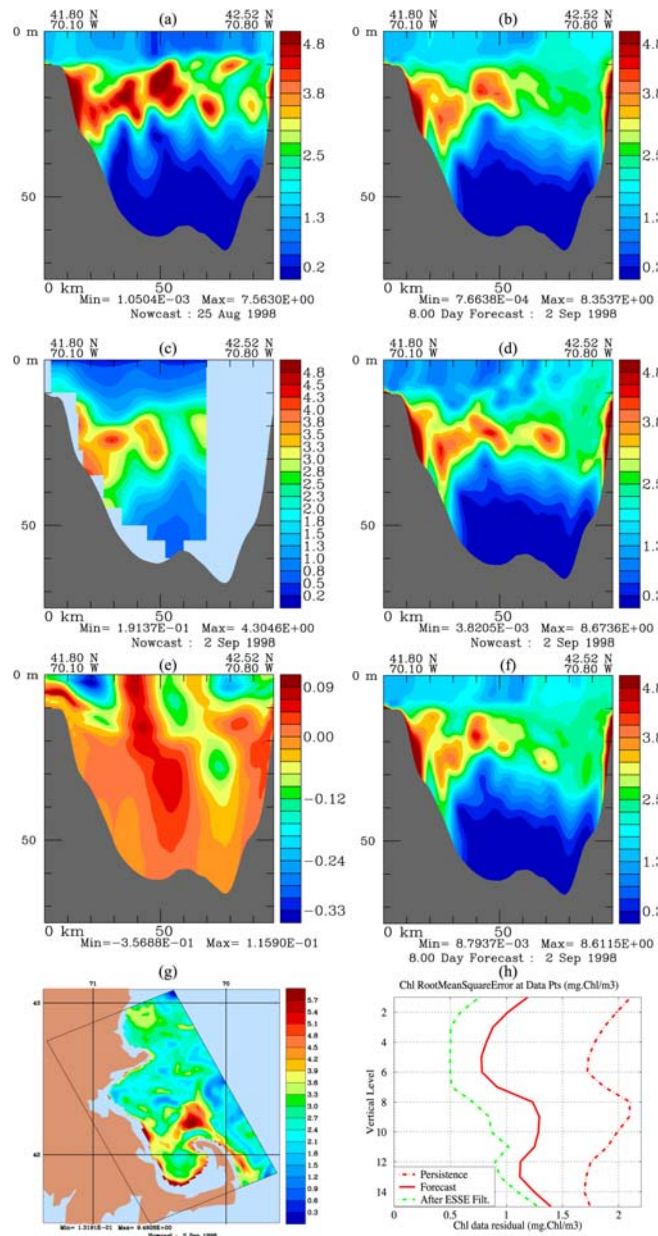


Fig. 8. Panels (a–f): Cross-sections in Chl-a fields, from south to north along the main axis of Massachusetts Bay, with, a) Nowcast conditions on Aug. 25; b) Forecast for Sep. 2; c) 2D objective analysis for Sep. 2 of the Chl-a data collected on Sep. 2–3; d) ESSE filtering estimate on Sep. 2; e) Difference between ESSE smoothing estimate on Aug. 25 and nowcast on Aug. 25; f) Forecast for Sep. 2, starting from ESSE smoothing estimate on Aug. 25. Panel (g): as d), but for Chl-a at 20 m depth. Panel (h): RMS differences between the Chl-a data on Sep. 2 and the field estimates at these data-points as a function of depth (specifically, "RMS-error" for persistence, dynamical forecast and ESSE