General features and climatology of marine boundary layers

Bretherton - Lecture 14

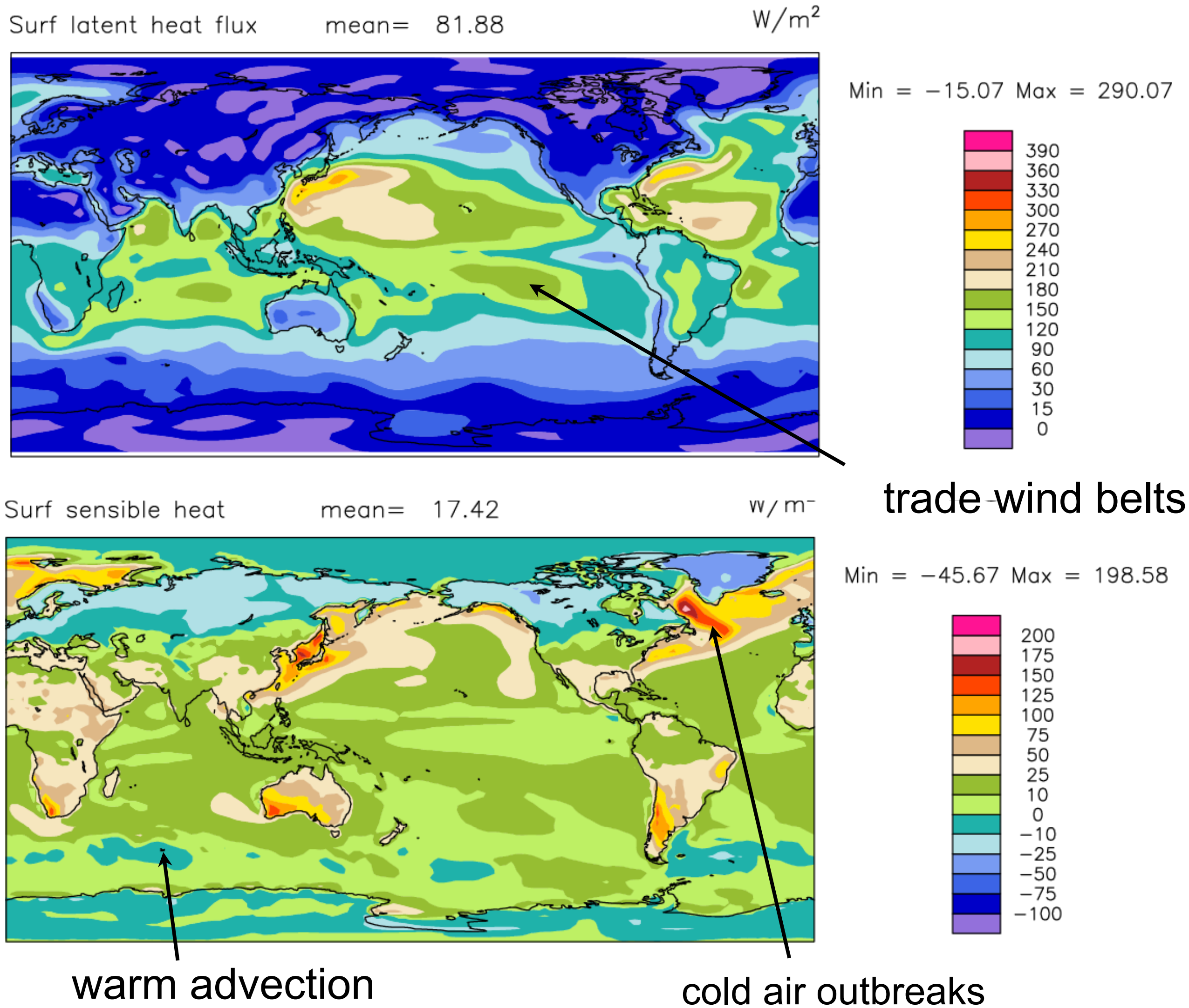
Differences between marine and continental atmospheric boundary layers

1. Near-surface air is always moist, with a typical relative humidity (RH) of 75-100%.
2. The diurnal cycle tends to be weak (though not negligible), since surface energy fluxes get distributed over a considerable depth (10-100+ m) of water, which has a heat capacity as much as hundreds of times as large as the atmospheric boundary layer.
3. Air-sea temperature differences tend to be small, except near coasts. The air tends to be 0-2 K cooler than the water due to radiative cooling and advection, except where there are strong winds or large sea-surface temperature (SST) gradients. The MBL air is usually radiatively cooling at 1-2 K/day, and some of this heat is supplied by sensible heat fluxes off the ocean surface. If the air is much colder than the SST, vigorous convection will quickly reduce the temperature difference.

Differences between marine and continental atmospheric boundary layers

4. Due to the small air-sea temperature difference, the 'Bowen ratio' of sensible to latent heat flux tends to be small (typically 0.1 in the tropical oceans, and more variable in midlatitudes); latent heat fluxes are 50-200 W m^{-2}, while (except in cold air outbreaks off cold land-masses) sensible heat fluxes are 0-30 W m^{-2}

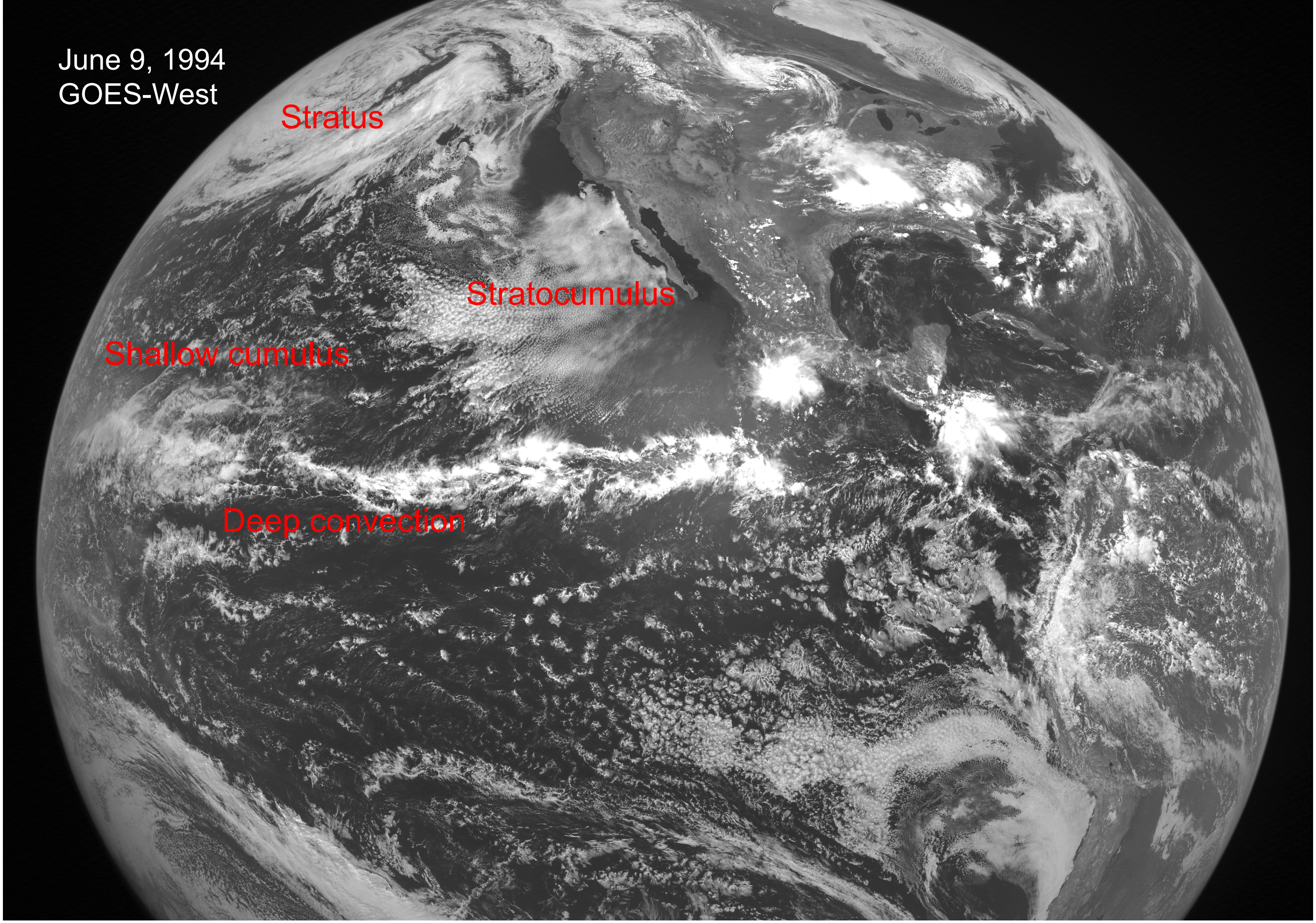
Surface fluxes (DJF)



Differences between marine and continental atmospheric boundary layers

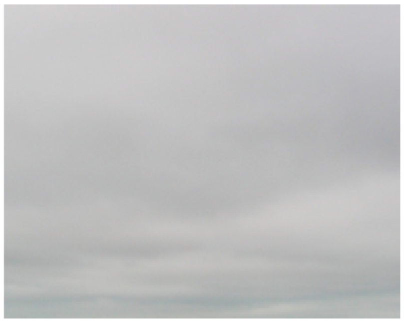
5. Over 95% of marine boundary layers contain cloud. The exceptions are near coasts, where warm, dry continental air is advected over a colder ocean, and in some regions (such as over the cold water upwelled along the equator in the eastern Pacific cold tongue) in which air is advecting from warmer to colder SST, tending to produce a more stable shear-driven BL which does not deepen to the LCL of surface air. Cloud can greatly affect MBL dynamics. It also affects the surface and top-of-atmosphere energy balance and the SST.

Marine boundary layer clouds from space



Marine Boundary Layer cloud types

Stratus (St)



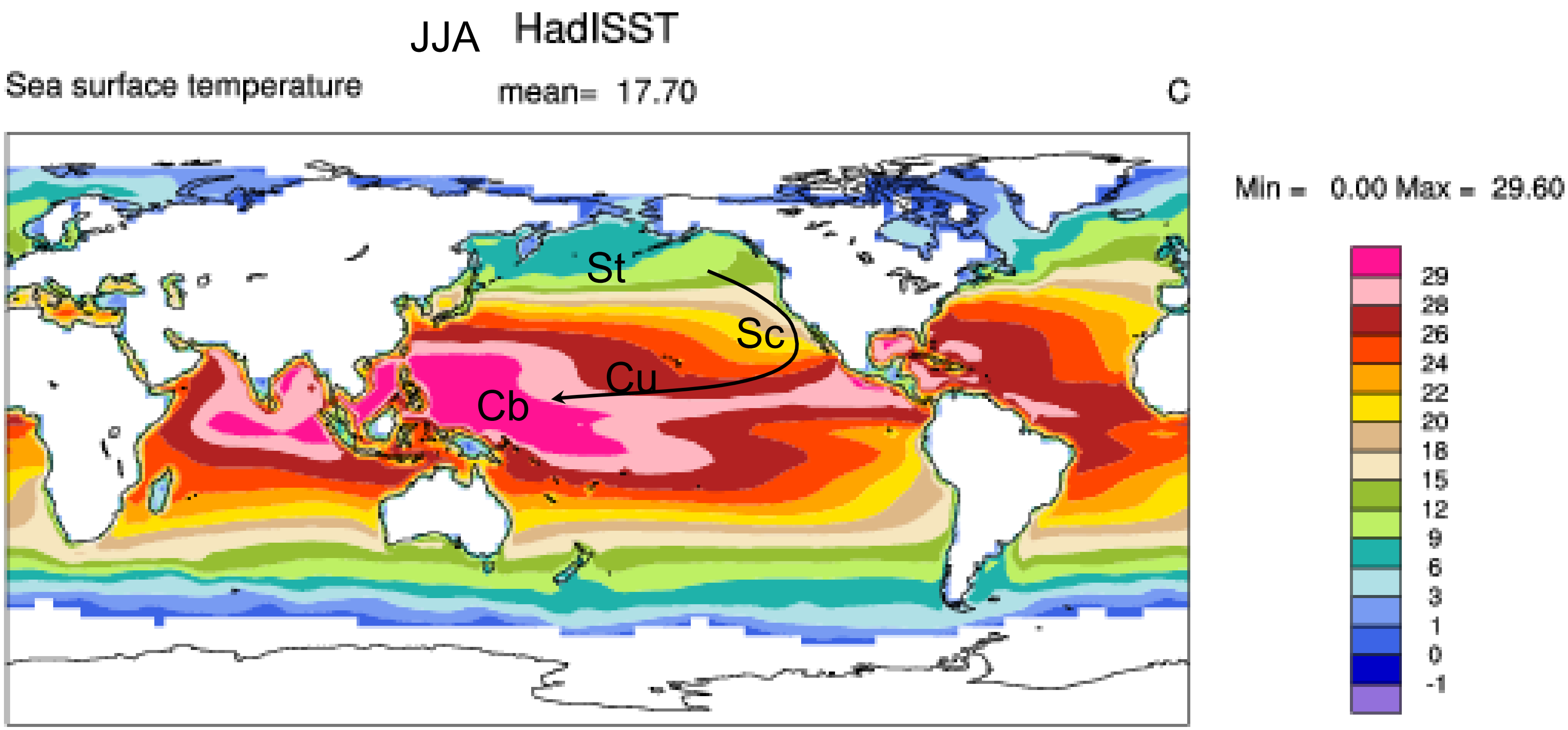
Stratocumulus (Sc)

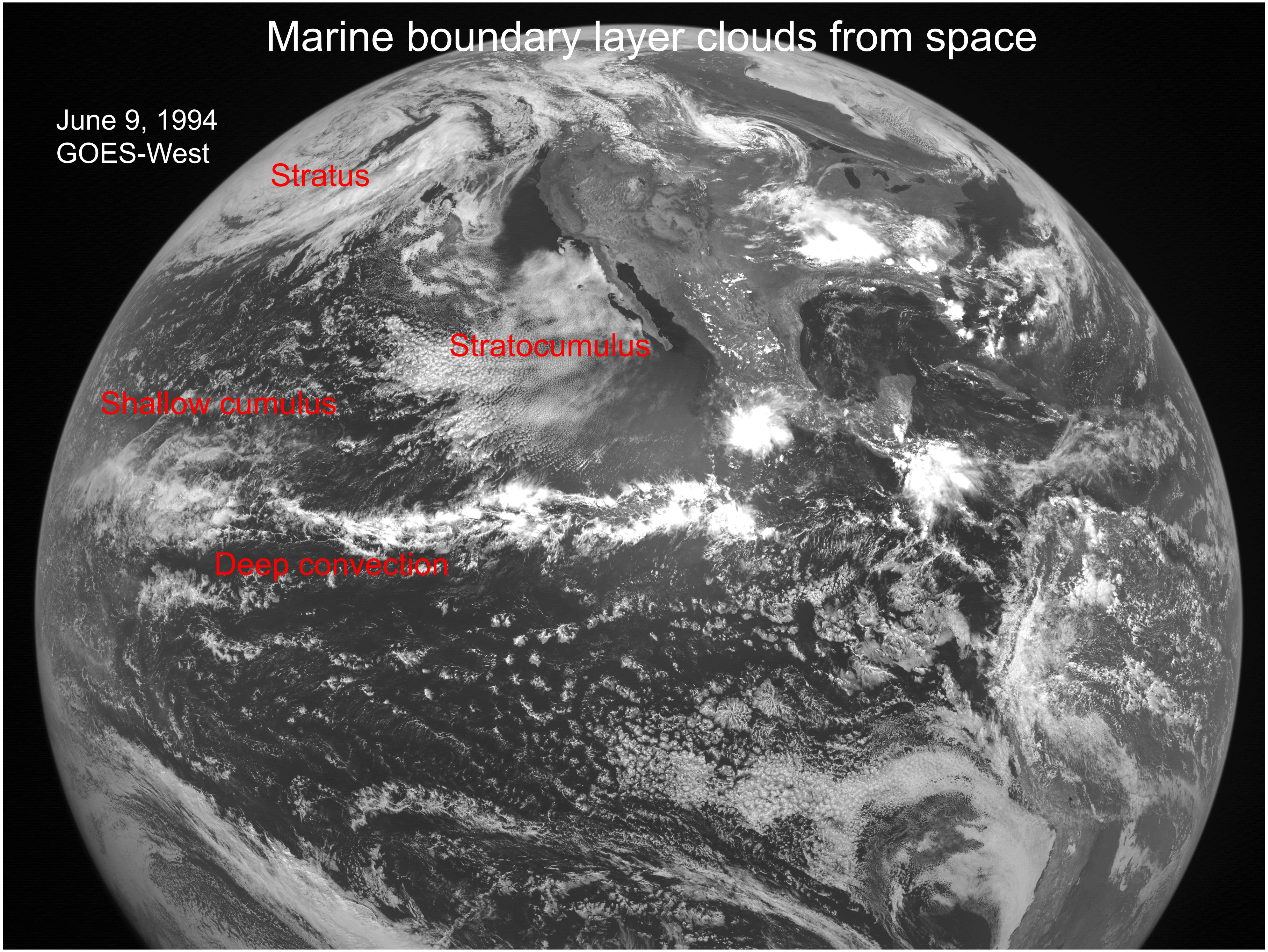
Cu under Sc

1. Stratus (St) and stratocumulus (Sc)-capped BLs, typically found in anticyclonic flow over the subtropical and midlatitude oceans, and often seen during the cool season over moister landmasses or in cold air outbreaks. These BLs may include Cu below or rising into the Sc.
2. Shallow cumulus (Cu) boundary layers, ubiquitous over oceanic trade-wind regimes, and often seen over land and midlatitude oceans as the later phase of cold air outbreaks
3. Boundary layers under deep convection, which have mesoscale variability associated with evaporating precipitation and downdrafts from cumulonimbus cloud systems
4. Fog and shallow stably-stratified stratus layers, often seen in midlatitudes in warm advection over cold water or in the Arctic over sea ice.

Observations over the oceans

- Transition from Sc - shallow Cu - deep Cu as temperature of sea-surface rises compared to that of mid-troposphere.




Marine boundary layer clouds from space
June 9, 1994
GOES-West
Stratus
Stratocumulus
Shallow cumulus
Deep convection

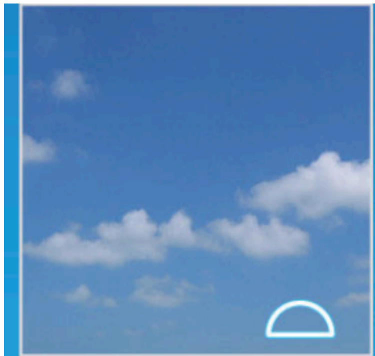
The global distribution of low cloud (at heights of 2 km or less above the surface) is documented in routine synoptic observations of cloud type and cover by using a simple visual classification scheme from the World Meteorological Organization (WMO).

TABLE 1. WMO low cloud classification.

C_L Code	Priority[a]	Nontechnical cloud type description
0	7	No stratocumulus, stratus, cumulus, or cumulonimbus
1 (small Cu)	6[b]	Cumulus with little vertical extent and seemingly flattened, or ragged cumulus other than of bad weather,[c] or both
2 (Cu)	5	Cumulus of moderate or strong vertical extent, generally with protuberances in the form of domes or towers, either accompanied or not by other cumulus or by stratocumulus, all having their bases at the same level
3	2	Cumulonimbus the summits of which, at least partially, lack sharp outlines, but are neither clearly fibrous (cirriform) nor in the form of an anvil; cumulus, stratocumulus, or stratus may also be present
4	3	Stratocumulus from the spreading out of cumulus; cumulus may also be present
5 (Sc)	6[b]	Stratocumulus not resulting from the spreading out of cumulus
6 (St)	6[b]	Stratus in a more or less continuous sheet or layer, or in ragged shreds, or both, but no stratus fractus of bad weather[c]
7 (Fs)	6[b]	Stratus fractus of bad weather[c] or cumulus fractus of bad weather, or both (pannus), usually below altostratus or nimbostratus
8 (Cu-under-Sc)	4	Cumulus and stratocumulus other than that formed from the spreading out of cumulus; the base of the cumulus is at a different level than that of the stratocumulus
9	1	Cumulonimbus, the upper part of which is clearly fibrous (cirriform), often in the form of an anvil, either accompanied or not by cumulonimbus without anvil or fibrous upper part, by cumulus, stratocumulus, stratus, or pannus

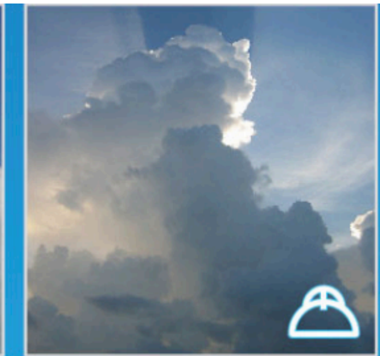
[a] 1 is highest priority and 7 is lowest priority in designating C_L if more than one type is present.
[b] If no C_L 2, 3, 4, 8, or 9 is present, priority is determined by whatever type has the greatest sky cover.
[c] "Bad weather" denotes the conditions that generally exist during precipitation and a short time before and after.

Norris 1998b (J. Climate)



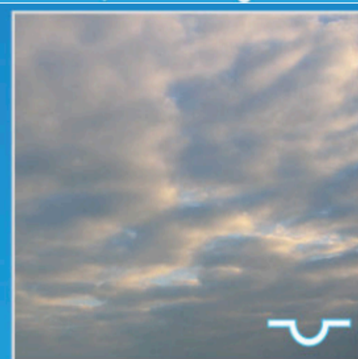
L1: Cumulus
Cumulus of fair weather with flattened appearance

L2: Cumulus
Moderate/strong vertical extent, or towering cumulus

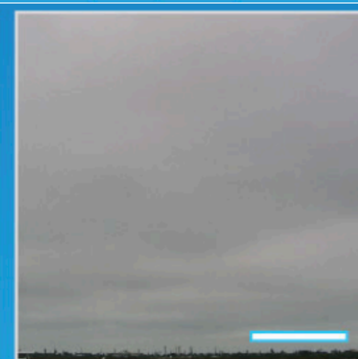


L3: Cumulonimbus
Tops not fibrous, outline not completely sharp, no anvil

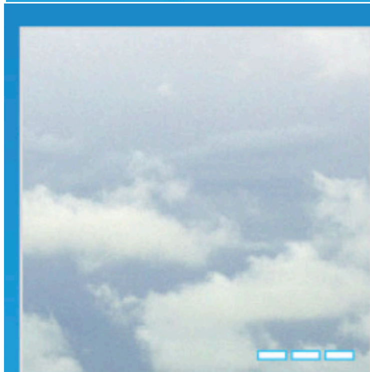
L4: Stratocumulus
From the spreading and flattening of cumulus



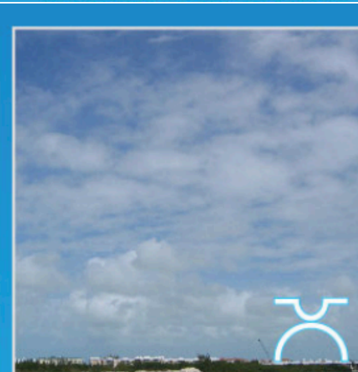
L5: Stratocumulus
Not from the spreading and flattening of cumulus



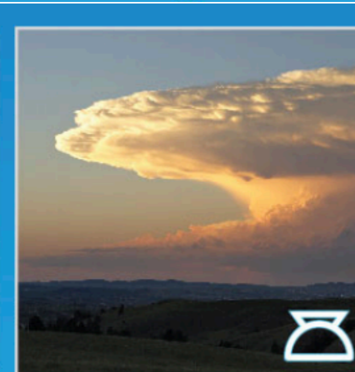
L6: Stratus
In a continuous layer and/or ragged shreds



L7: Stratus Fractus
and/or Cumulus Fractus occurs with rain or snow



L8: Cumulus & Stratocumulus
Not spreading, bases at different levels



L9: Cumulonimbus
With fibrous top, often with an anvil

www.weather.gov

Norris 1998a (J. Climate)

Surface cloud observations and coincident surface meteorological observations and soundings from five ocean weather stations are used to establish representative relationships between low cloud type and marine boundary layer (MBL) properties for the subtropics and midlatitudes by compositing soundings and meteorological observations for which the same low cloud type was observed.

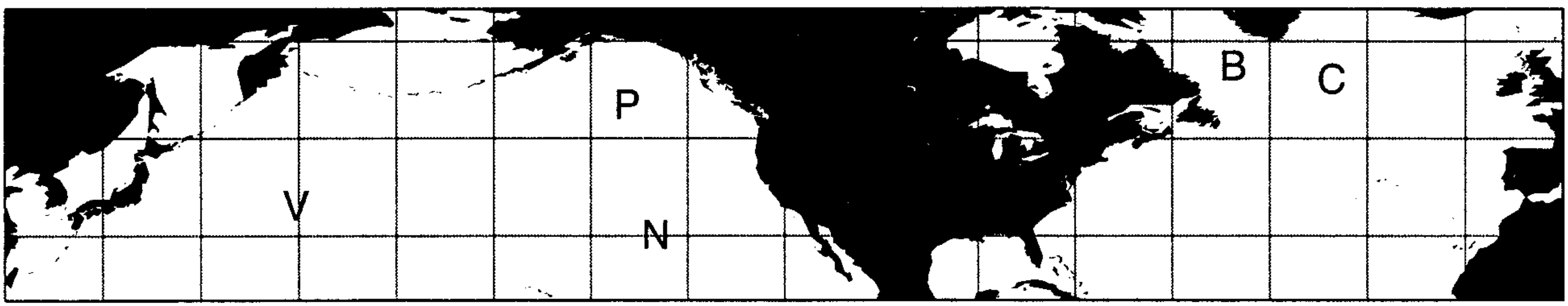


FIG. 1. Locations of OWS B (56.5°N, 51°W), C (52.75°N, 35.5°W), N (30°N, 140°W), P (50°N, 145°W), and V (34°N, 164°E), which contributed soundings and surface observations for this investigation.

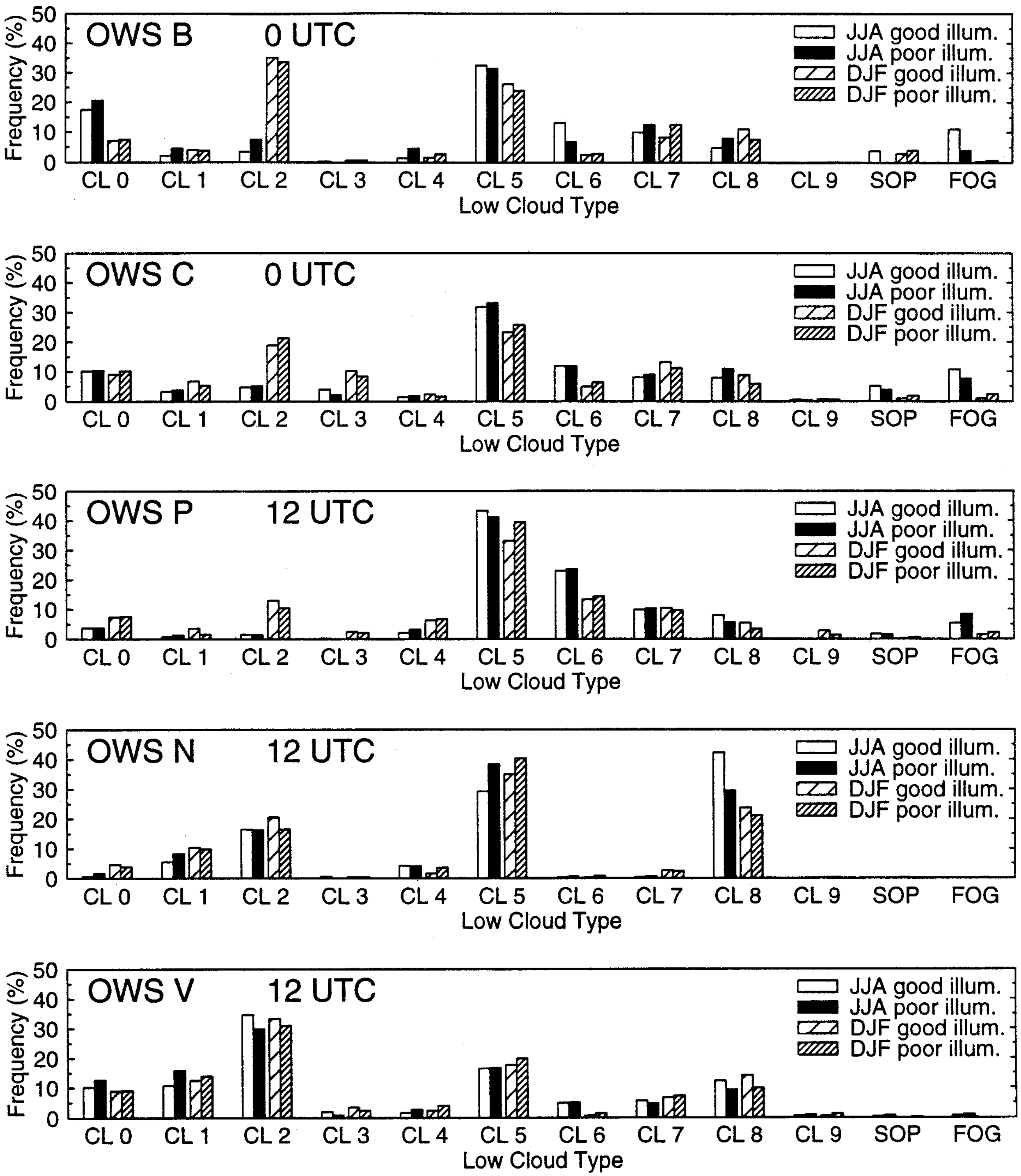


FIG. 2. Frequency of occurrence of the low cloud types described in Table 1 along with sky-obscuring precipitation (SOP) and sky-obscuring fog (FOG) at OWS B, C, N, P, and V during JJA and DJF. Observations are from 0000 UTC or 1200 UTC under conditions of good illumination and poor illumination according to the criterion of Hahn et al. (1995). Color coding of bar: white—JJA, good illumination; black—JJA, poor illumination; light hatching—DJF, good illumination; dense hatching—DJF, poor illumination.

SOP =
Sky Obscuring Precipitation

FOG =
Sky Obscuring FOG

Norris 1998a (J. Climate)

The Voluntary Observing Ship (VOS) Program

GOT WEATHER?

Report It!
"Observations Save Lives"

Only You Know The Weather
At Your Position

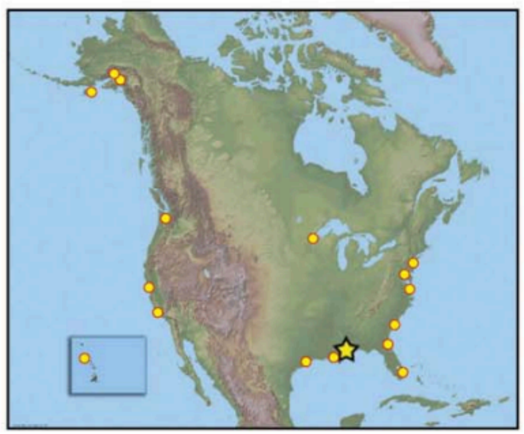
Report Weather at: 0000, 0600, 1200 & 1800 UTC to the National Weather Service.
For detailed information about the program, contact one of the Port Meteorological Officers
or
The National Program Center
Phone: (228) 688-1457/1818
E-Mail: VOS.NOAA.GOV
or visit
www.vos.noaa.gov

PMO LOCATIONS & CONTACTS

Port Meteorological Officers (PMOs) are located in the following United States ports and should be contacted when services are needed or if your vessel would like to receive more information about participating.
(* is the National Program Office):

Anchorage, AK	907-271-5137	PMOANC@noaa.gov
Baltimore, MD	410-633-4709	PMOBAL@noaa.gov
Charleston, SC	843-740-1281	PMOCHS@noaa.gov
Duluth, MN	218-729-0651	PMOGLAKES@noaa.gov
Honolulu, HI	808-532-6439	PMOHON@noaa.gov
Houston, TX	281-534-2640 x277	PMOHOU@noaa.gov
Jacksonville, FL	904-607-3219 x117	PMOJAX@noaa.gov
Kodiak, AK	907-487-2102	PMOKDK@noaa.gov
Los Angeles, CA	562-980-4090	PMOLAX@noaa.gov
Ft. Lauderdale, FL	954-463-4271	PMOMIA@noaa.gov
Newark, NJ/NY	732-316-5409	PMONYC@noaa.gov
New Orleans, LA	504-289-2294	PMOMSY@noaa.gov
Norfolk, VA	757-877-1692	PMONOR@noaa.gov
Oakland, CA	510-637-2960	PMOOAK@noaa.org
Seattle, WA	206-526-6100	PMOSEA@noaa.gov
Valdez, AK	907-835-4505	PMOVDZ@noaa.gov

***National Program Center**
Stennis Space Center, MS
228-688-1457 or 1818



VOS

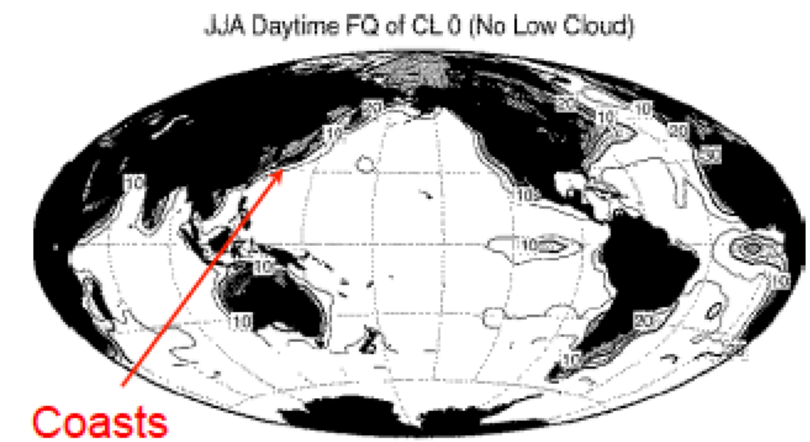
VOLUNTARY OBSERVING SHIP PROGRAM

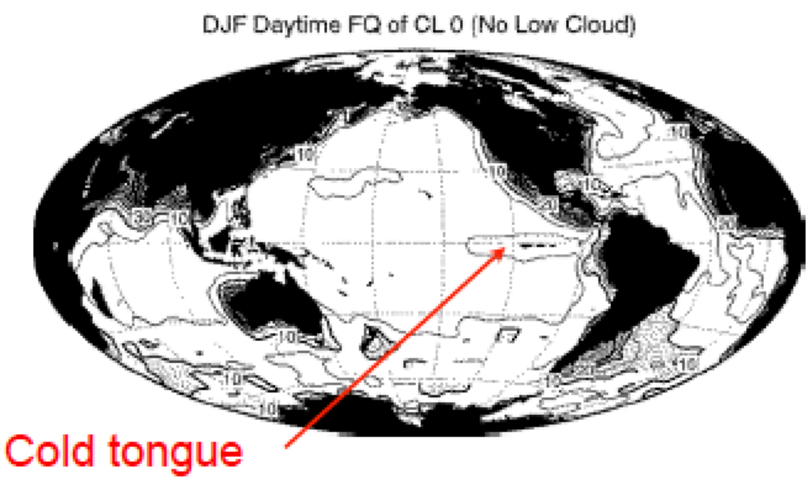
U.S. DEPARTMENT OF COMMERCE

National Oceanic and Atmospheric Administration

National Weather Service

C_L 0 (No cloud)





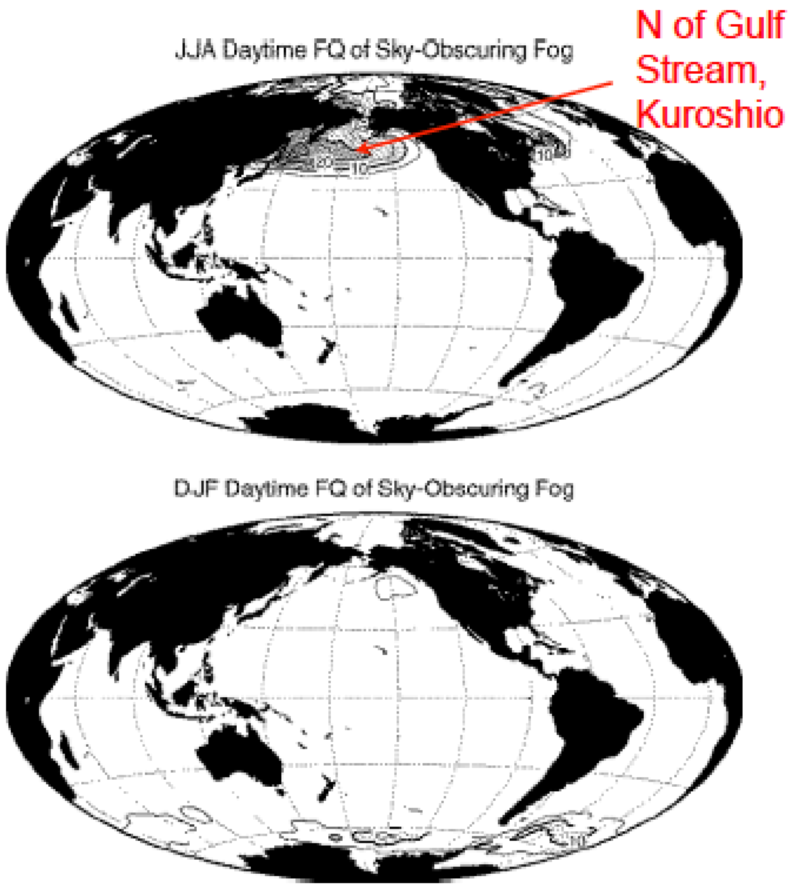
C_L 0 is very frequent adjacent to continents, over the Mediterranean Sea, and over the Arctic Ocean, and sometimes occurs poleward and eastward of continents at midlatitudes during summer, where poleward and eastward is usually downwind.

C_L 0 is associated with warm advection of dry air from land.

C_L 0 also sometimes occurs on the southern side of the equatorial cold tongue in the Pacific and Atlantic Oceans where southerly winds advect air over colder SST.

Norris 1998b (J. Climate)

Sky-obscuring fog

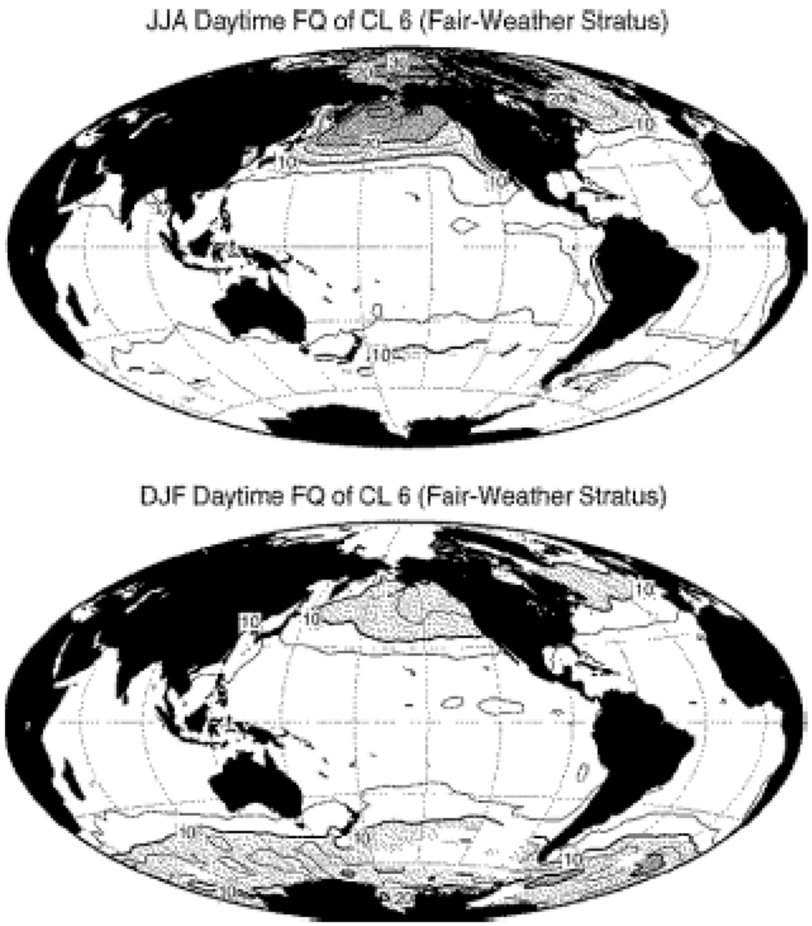


Sky-obscuring fog is rare over most of the ocean except in the western midlatitude North Pacific and North Atlantic and parts of the Arctic during summer where substantial warm advection occurs. The maximum frequency of sky-obscuring fog occurs where mean warm advection (including eddy terms) is greatest.

Norris 1998b (J. Climate)

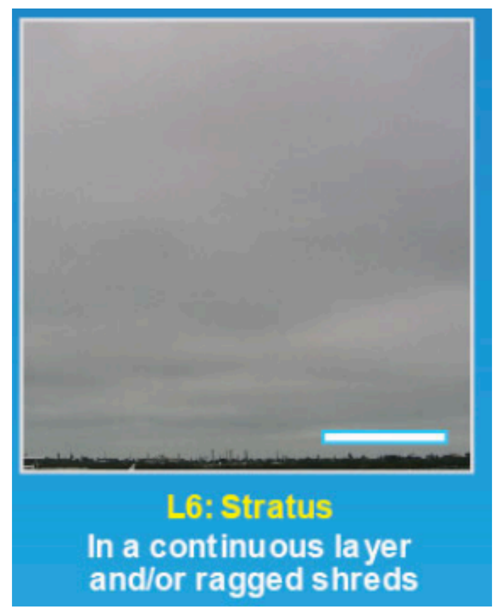
CL 6 (Fair weather Stratus)

Weak air-sea temperature differences



Norris 1998b (J. Climate)

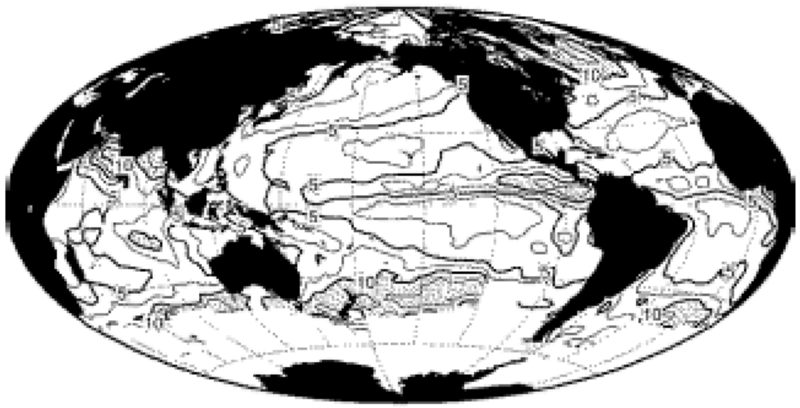
The frequency which observers report the dominant cloud type is stratus. This tends to form under high pressure without strong surface heating. It favor cold oceans during the summer.



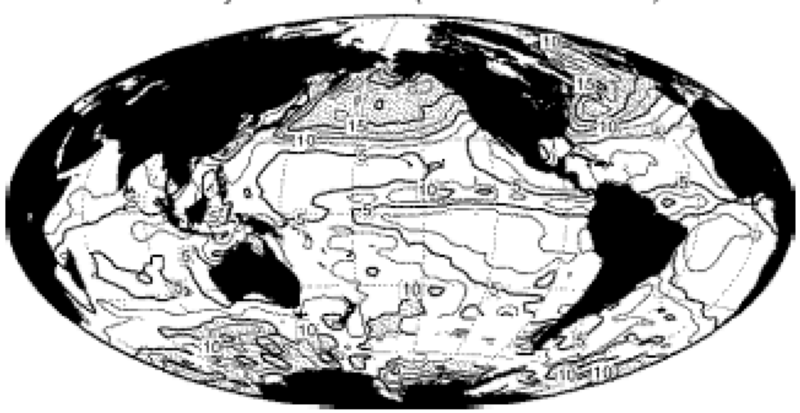
CL 7 (Bad weather Stratus)

Deep storm systems

JJA Daytime FQ of CL 7 (Bad-Weather Stratus)

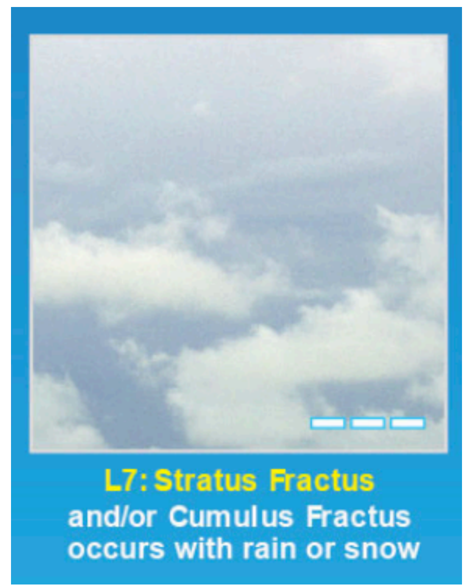


DJF Daytime FQ of CL 7 (Bad-Weather Stratus)

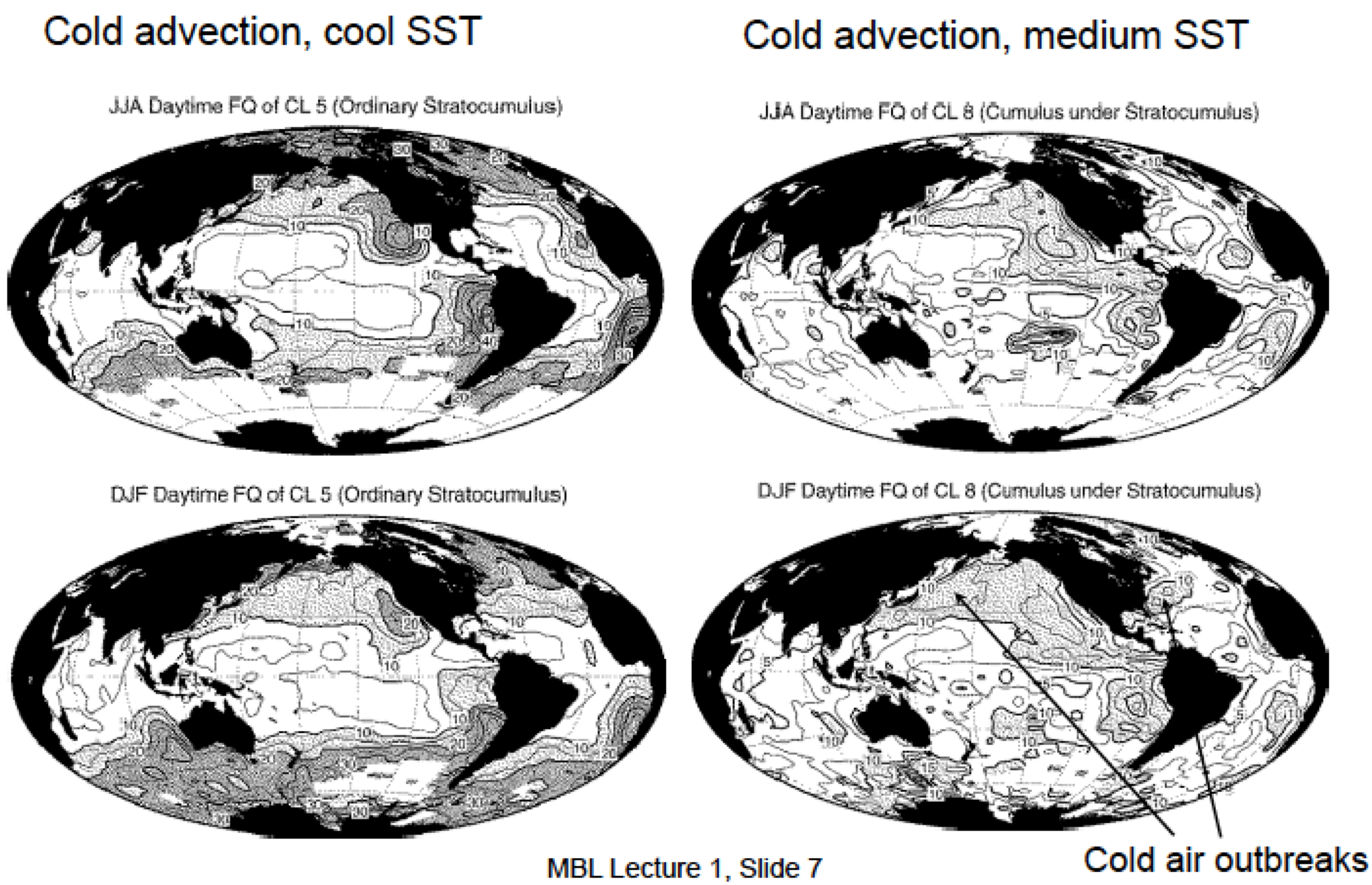


Norris 1998b (J. Climate)

Bad-weather stratus reflecting precipitation. It tends to reflect the rainfall distribution, and occurs relatively infrequently over the summer midlatitude oceans when normal stratus is maximum.



Cloud types that indicate cold advection over cool SSTs (Sc) and warmer SSTs (cumulus under stratus). These cloud types correspond to convective boundary layers with upward surface heat fluxes. Here ‘cool’ and ‘warm’ are relative to the overlying troposphere, so in a cold air outbreak, the ocean may be relatively warm compared to the air aloft and favor a Cu-under-Sc boundary layer.

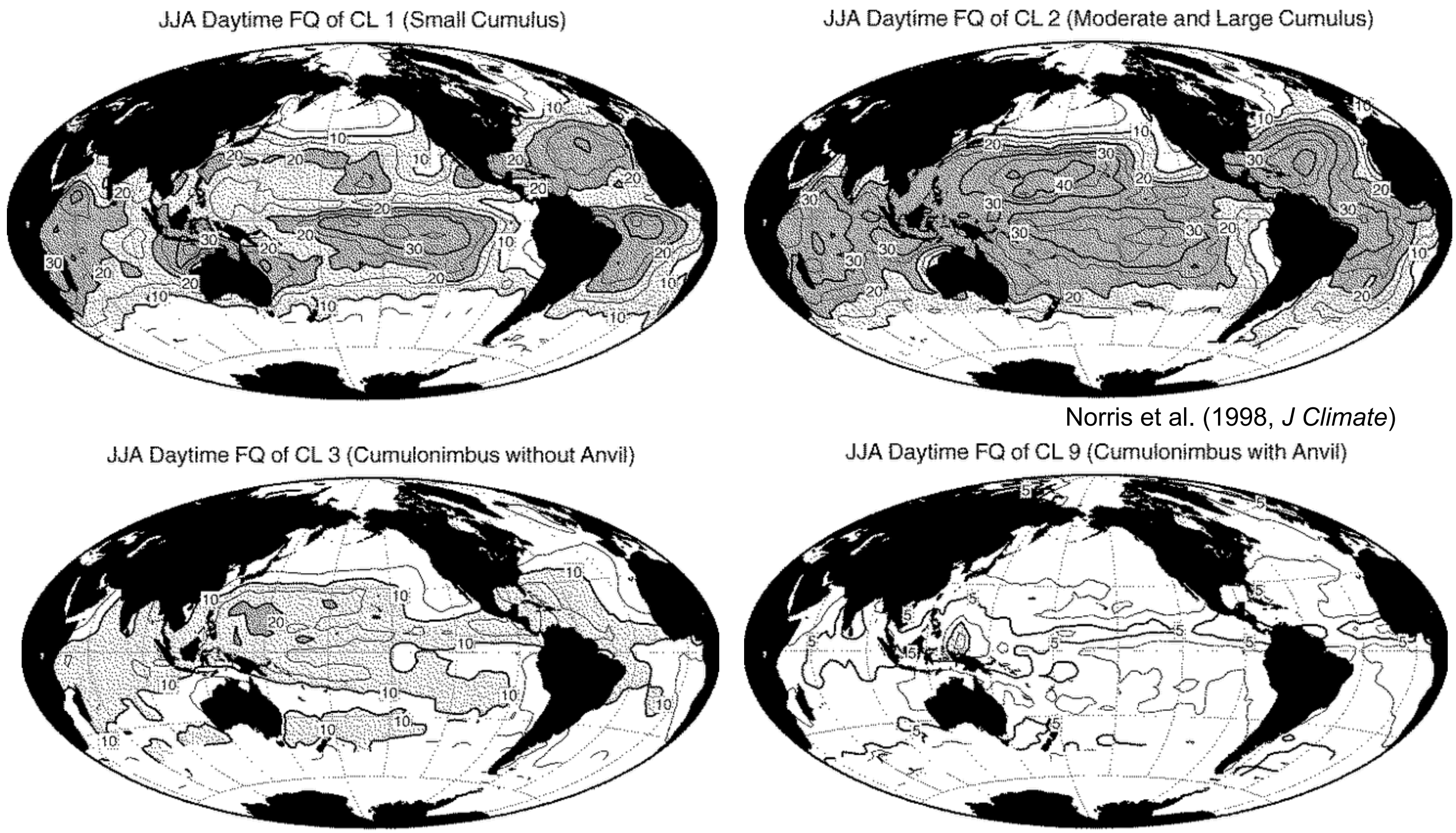


Norris 1998b (J. Climate)

The various cumulus cloud types, which favor warm SSTs.

Here ‘cool’ and ‘warm’ are relative to the overlying troposphere.

Cumulus-topped MBLs



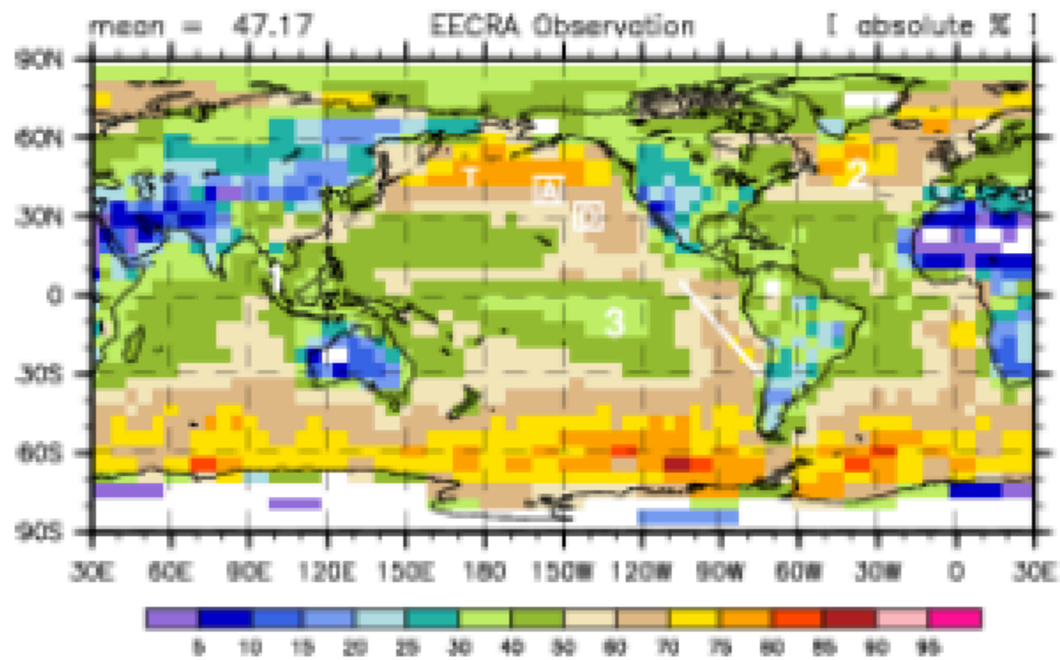
Norris et al. (1998, *J Climate*)

Over warm oceans, Cu-topped MBLs > 70% of time.

Norris 1998b (J. Climate)

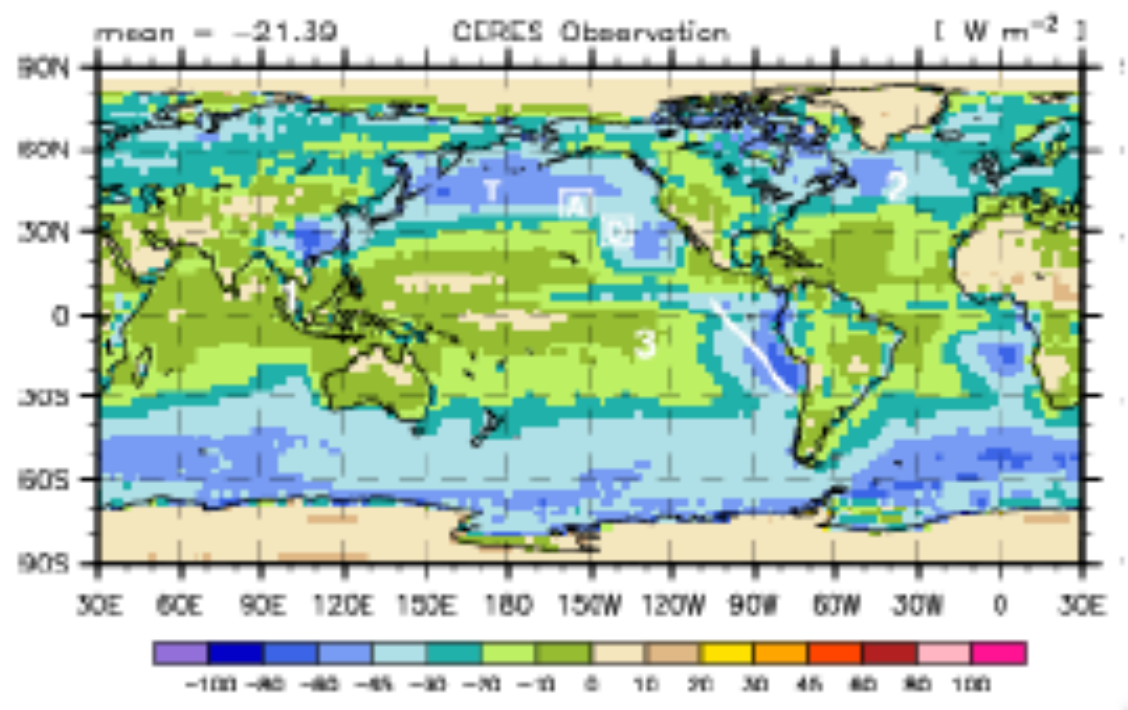
The annually averaged cloud cover (frequency of occurrence multiplied by fractional sky cover when cloud type is present) for `stratus' (stratus+ stratocumulus+fog), which encompasses the most radiatively important cloud types, since cumulus cloud only has a typical sky cover of 20%. Stratus cloud layers are typically 100-500 m thick, with a cloud base anywhere from the surface to 1500 m, and mostly do not precipitate much. Over much of the midlatitude oceans and parts of the eastern subtropical oceans, stratus cloud cover exceeds 50%. In some parts of the Aleutian Islands, the average stratus cloud cover in June, July and August is 90%. Over land, there is much less stratus cloud due to the lesser availability of surface water. In most of the tropical and subtropical oceans, stratus clouds are rare, as we saw in previous slides.

Stratus cloud amount (%)



‘net cloud radiative effect’, the change to the net downward radiation at the top of the atmosphere induced by clouds. For boundary layer cloud, net CRE is mainly due to the reflection of sunlight by the cloud, which reduced net downward radiation at TOA and causes negative CRE. The longwave cloud radiative effect is small since being low clouds, stratus emit radiation at a similar temperature as the underlying surface. About 50% of the radiative cooling is realized in the ocean and 50% in the atmosphere. The atmosphere cools because of the longwave cooling of the clouds. The surface cools because the clouds shade the sunlight. The clouds emit longwave radiation downward that partly compensates for the shortwave cooling of the surface.

Net CRE [W m-2]



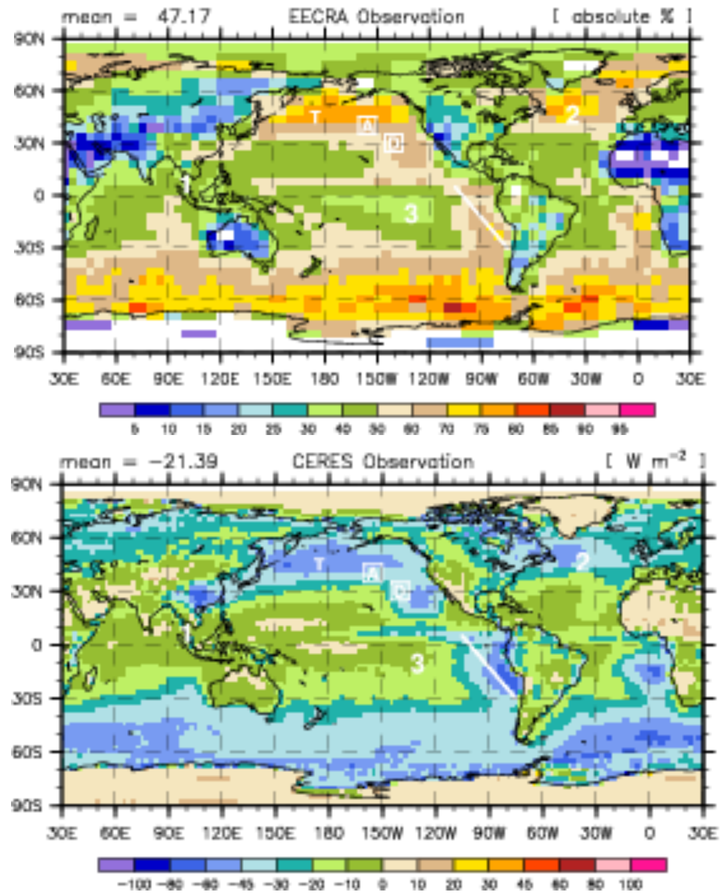
The net CRE is highly anticorrelated with stratus cloud amount because stratus clouds are reflective, having a typical albedo of 0.3-0.7.

Stratus cloud amount and net cloud radiative effect

Stratus cloud amount (%)

correlated with…

Net CRE [W m^{-2}]

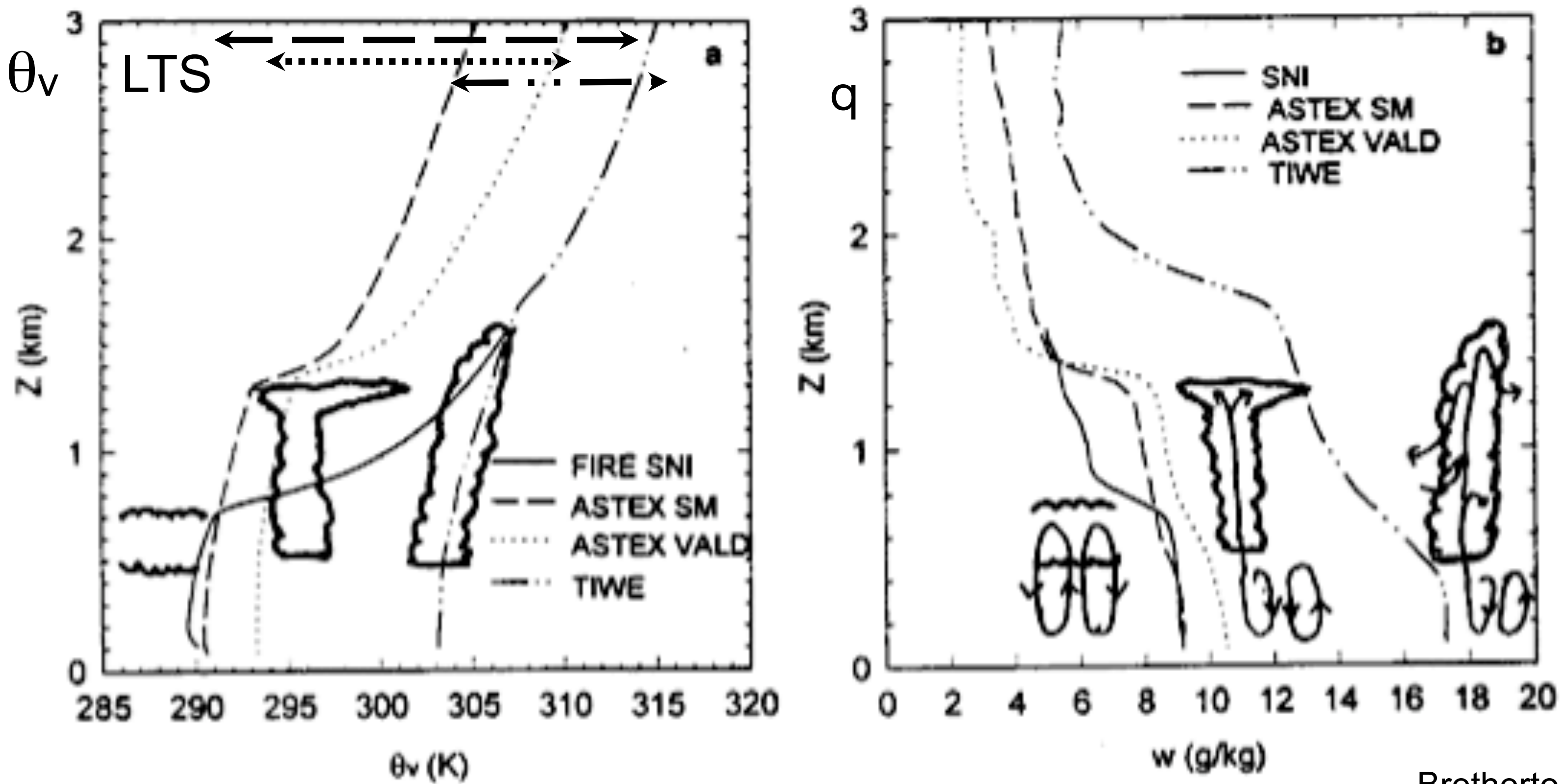


CRE = change in net (shortwave+longwave) radiation into TOA due to clouds.

Sc reflect sunlight and are too warm to much affect outgoing longwave radiation, producing a negative SWCRE and little LWCRE, for negative net CRE.

- Marine stratus cloud is the most radiatively important cloud type for the current climate.

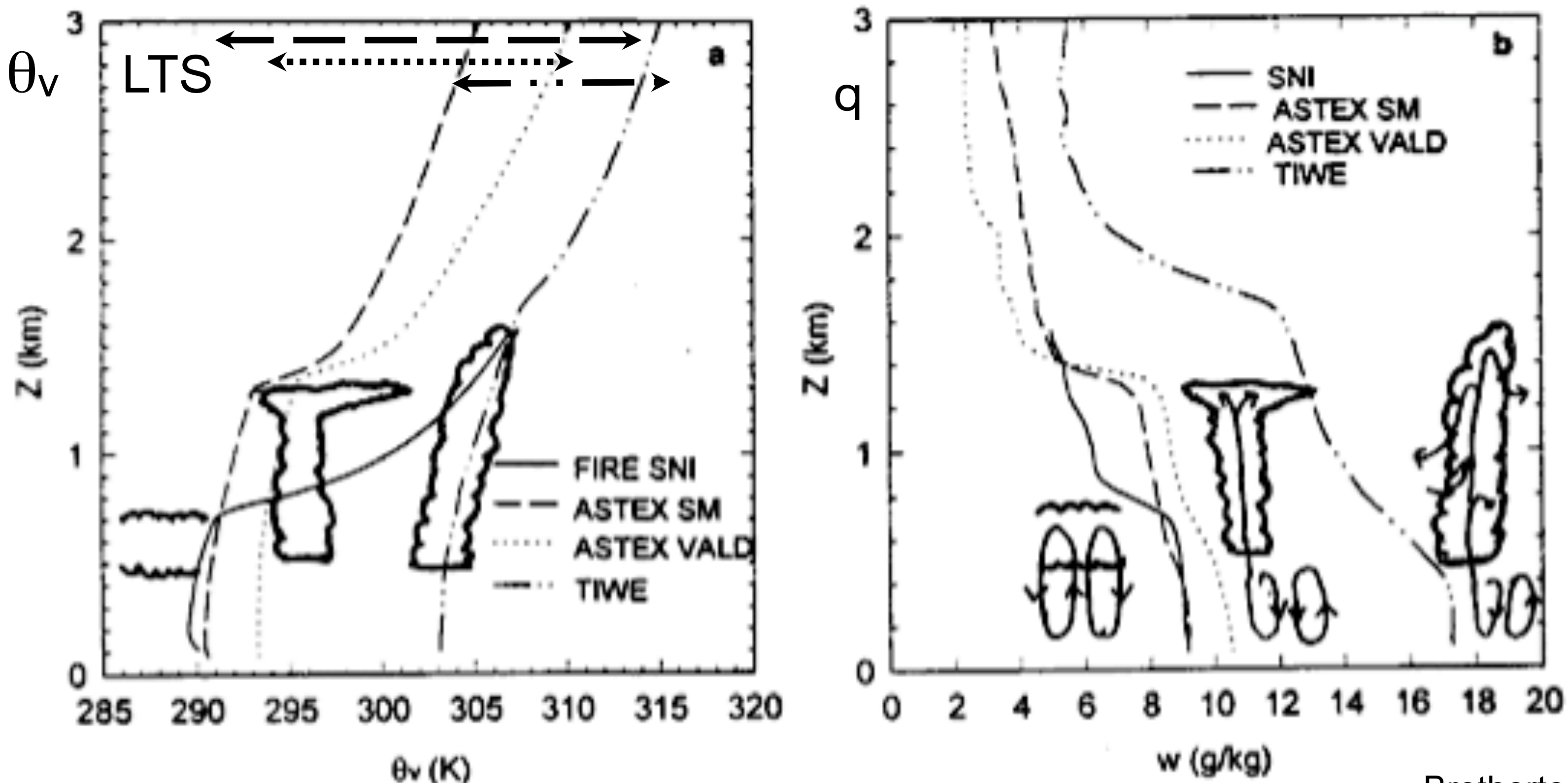
Subtropical PBL soundings



Bretherton 1997,
after Albrecht et al. 1995

Composite soundings from four field experiments that studied marine subtropical and tropical CTBLs. The experiments were conducted over locations with very different sea-surface temperature (SST). The typical observed boundary layer cloud structure and circulations are sketched.

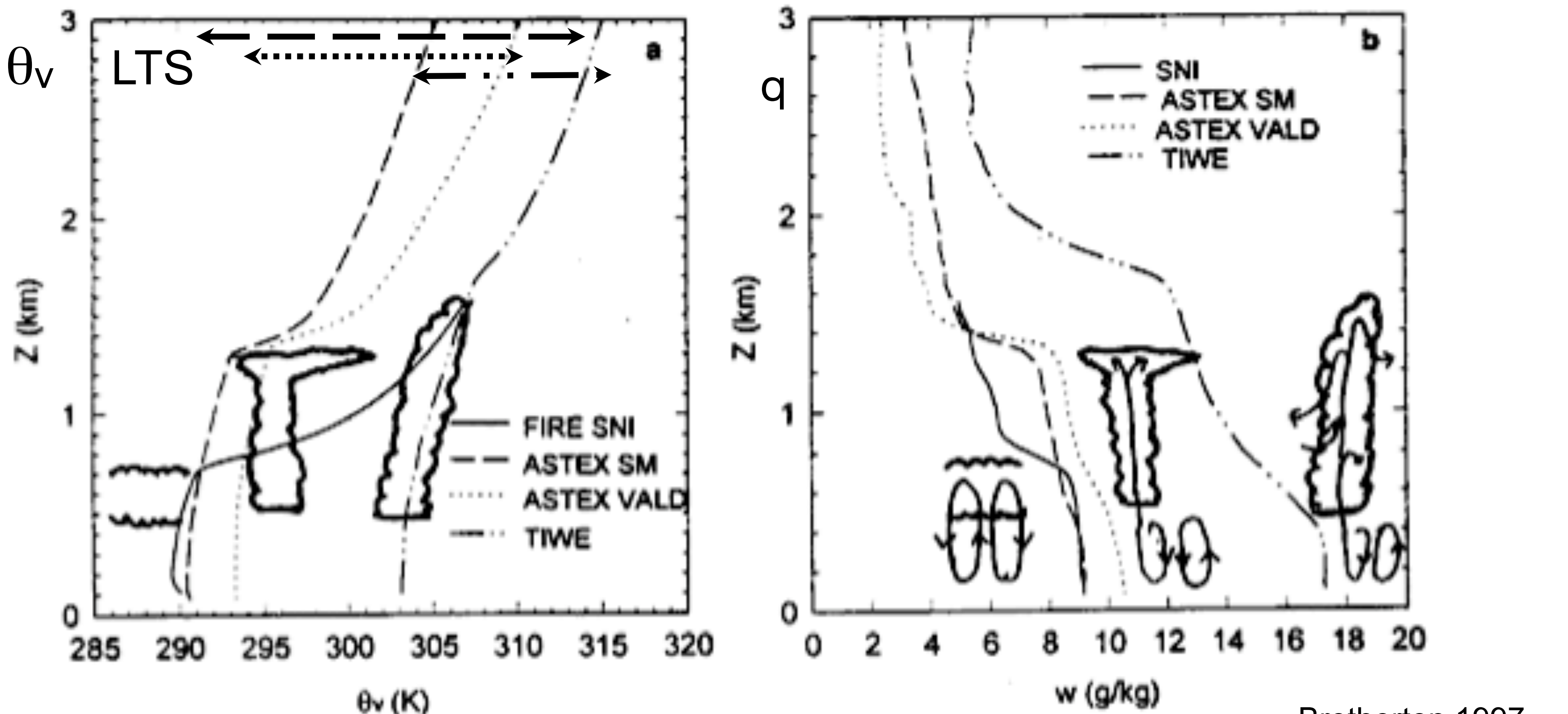
Subtropical PBL soundings



Bretherton 1997,
after Albrecht et al. 1995

The deeper BLs tend to have less cloud cover, a weaker inversion, and a less well-mixed structure in the total water mixing ratio w = vapor+liquid (which is conserved following fluid motions in the absence of mixing). The stratification of the virtual potential temperature θ_v is roughly dry-adiabatic below cloud base. In the cloud layer, it is moist-adiabatic within the shallow FIRE stratocumulus cloud layer and conditionally unstable in the other cases.

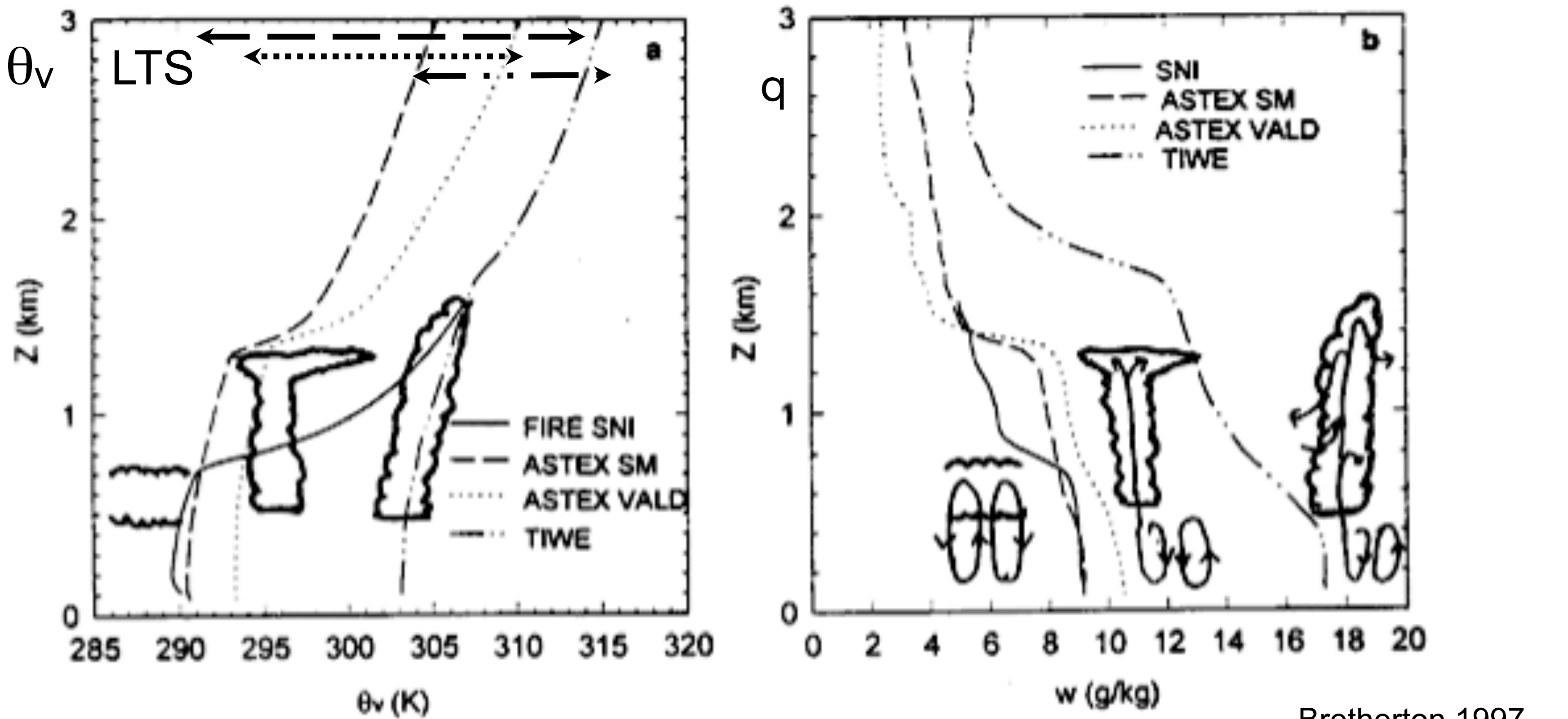
Subtropical PBL soundings



Bretherton 1997,
after Albrecht et al. 1995

The lower tropospheric stability (LTS) = θ(700 hPa) –θ(1000 hPa) correlates well with how shallow and strong the inversion is, as seen at the top of the figure. Hence it also correlates well with stratus cloud cover and net CRE in low latitudes.

Subtropical PBL soundings



Bretherton 1997,
after Albrecht et al. 1995

Stratocumulus and Stratus clouds favored by strong, low inversions, which go with large lower tropospheric stability

LTS = θ(700 hPa) –θ(1000 hPa).

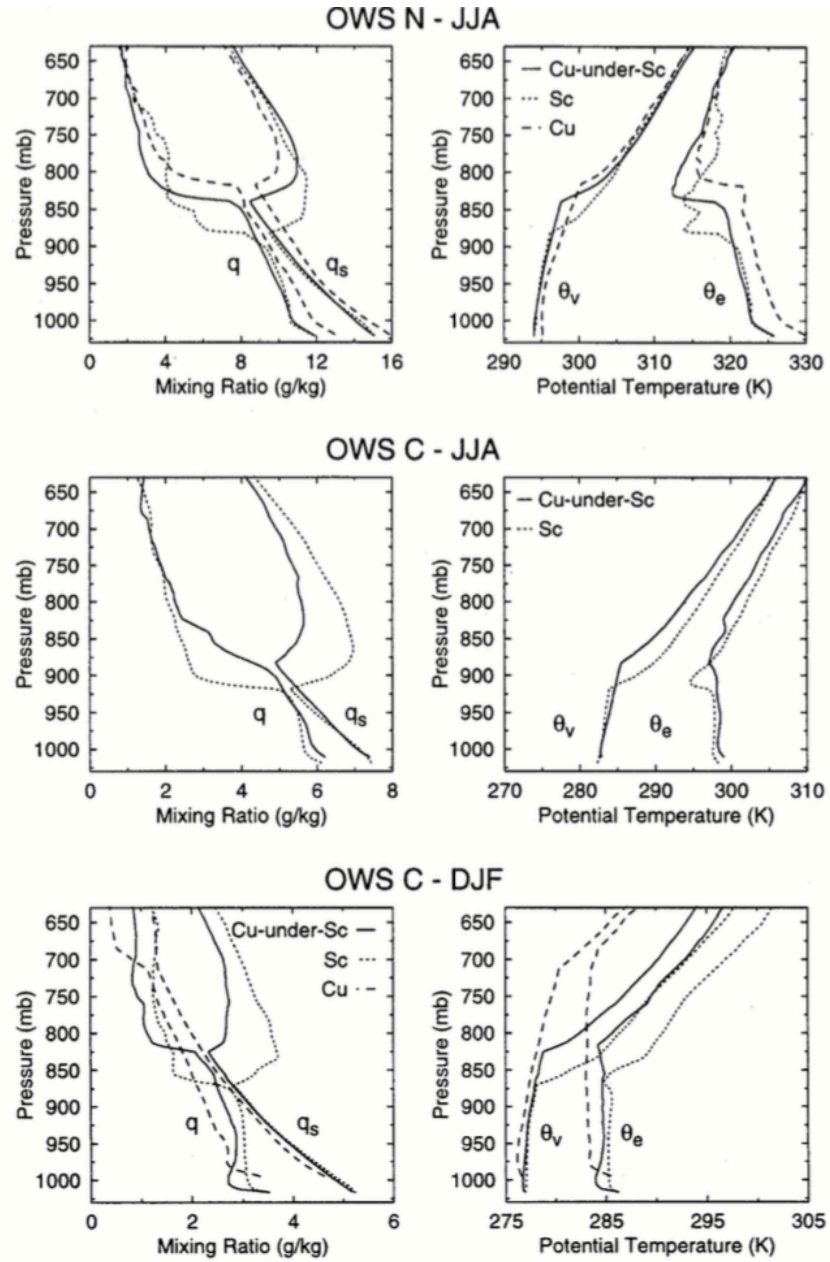
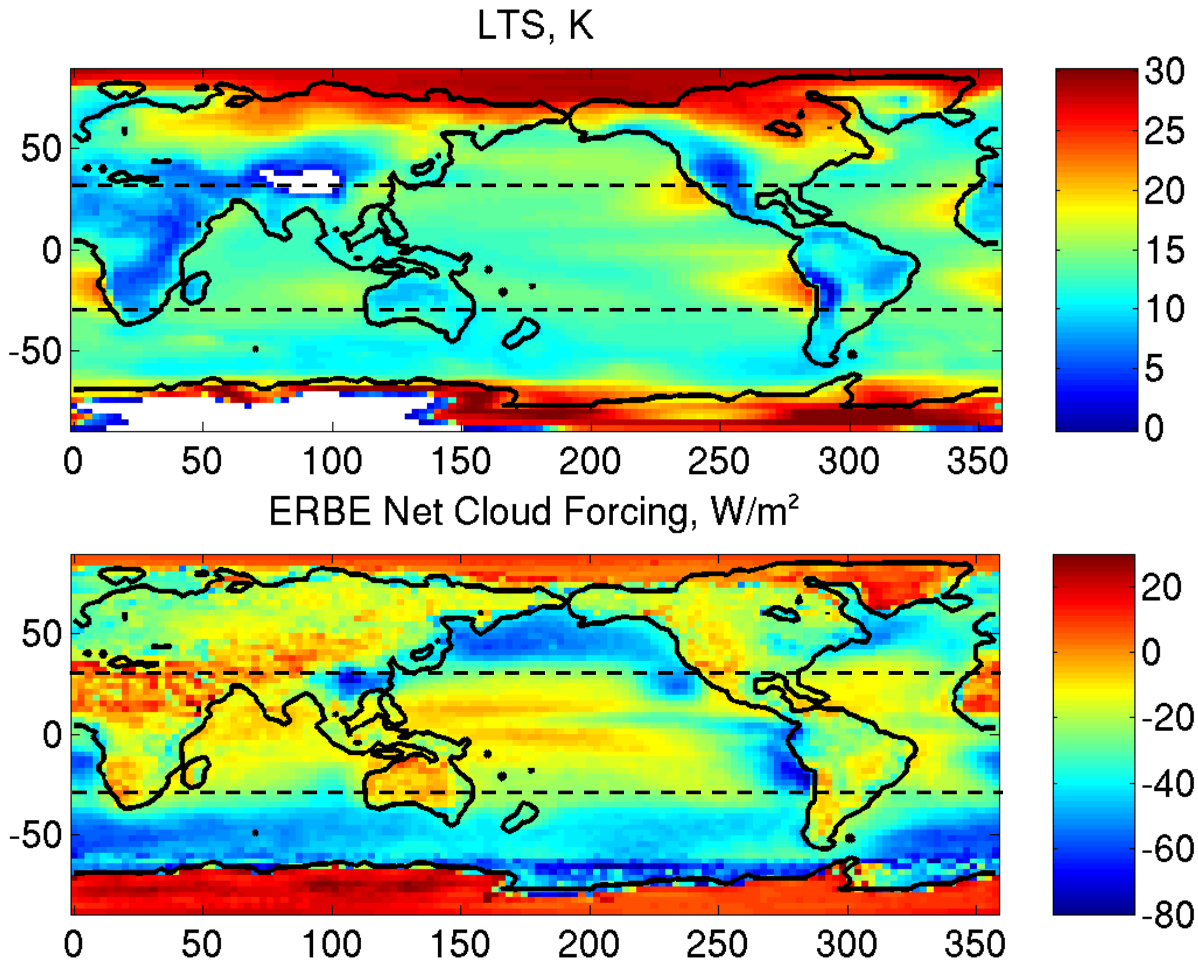


FIG. 3. Composite water vapor mixing ratio (q) and saturation water vapor mixing ratio (q_s) (left) and virtual potential temperature (θ_v) and equivalent potential temperature (θ_e) (right) for cumulus-under-stratocumulus (C_L 8) (solid), stratocumulus (C_L 5) (dotted), and moderate and large cumulus (C_L 2) (dashed) at OWS N during JJA (top), OWS C during JJA (middle), and OWS C during DJF (bottom).

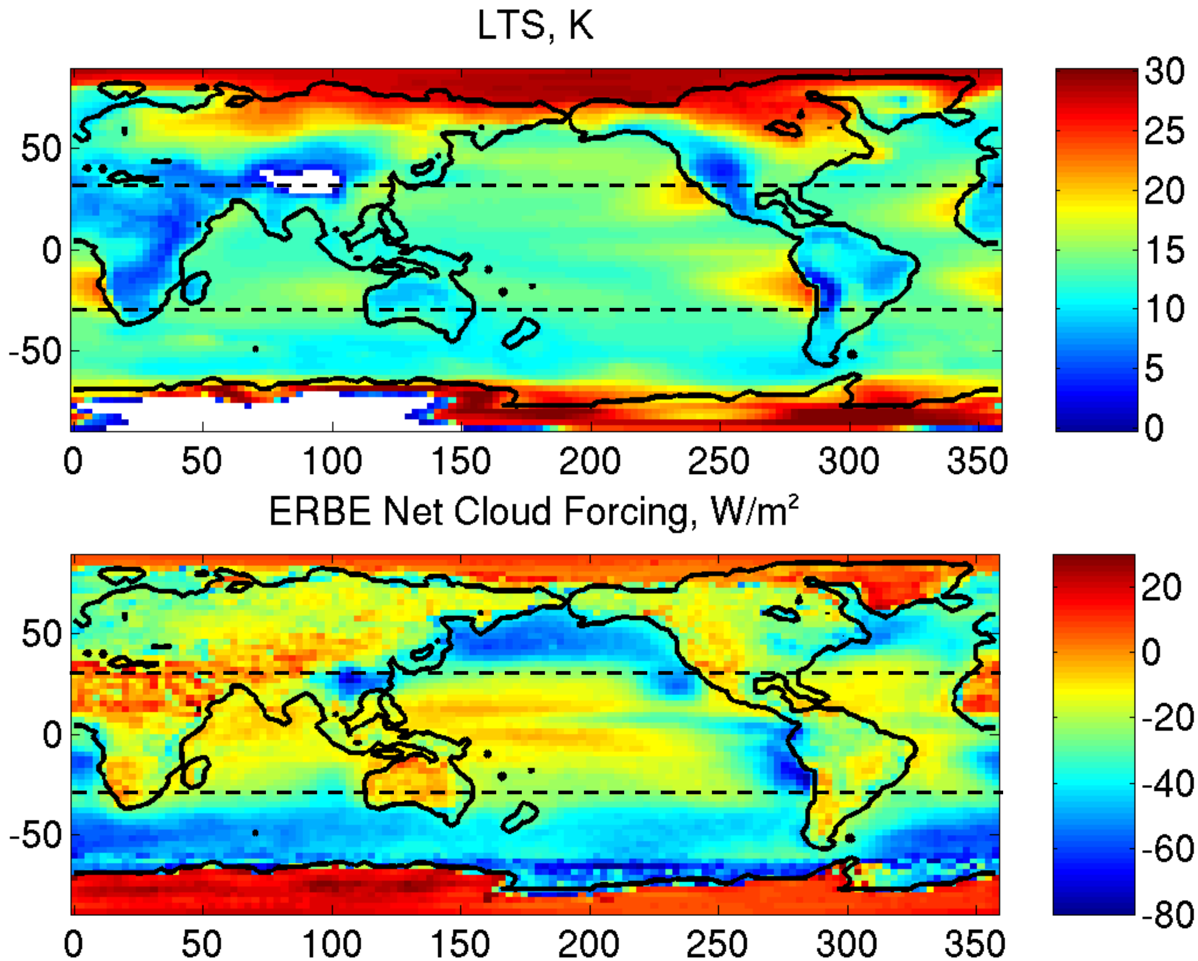
Norris 1998a (J. Climate)

Lower tropospheric stability



STL correlates well with stratus cloud cover and net CRE in low latitudes. This strong correlation between how cool the SST is compared to the free troposphere, the vertical structure of the boundary layer, its cloud cover, and its effect on the radiation budget is very important for climate, yet difficult for climate models to quantitatively reproduce.

Lower tropospheric stability



Geographically and seasonally correlated with subtropical marine stratus cloud cover and net CRE (Klein & Hartmann 1993)